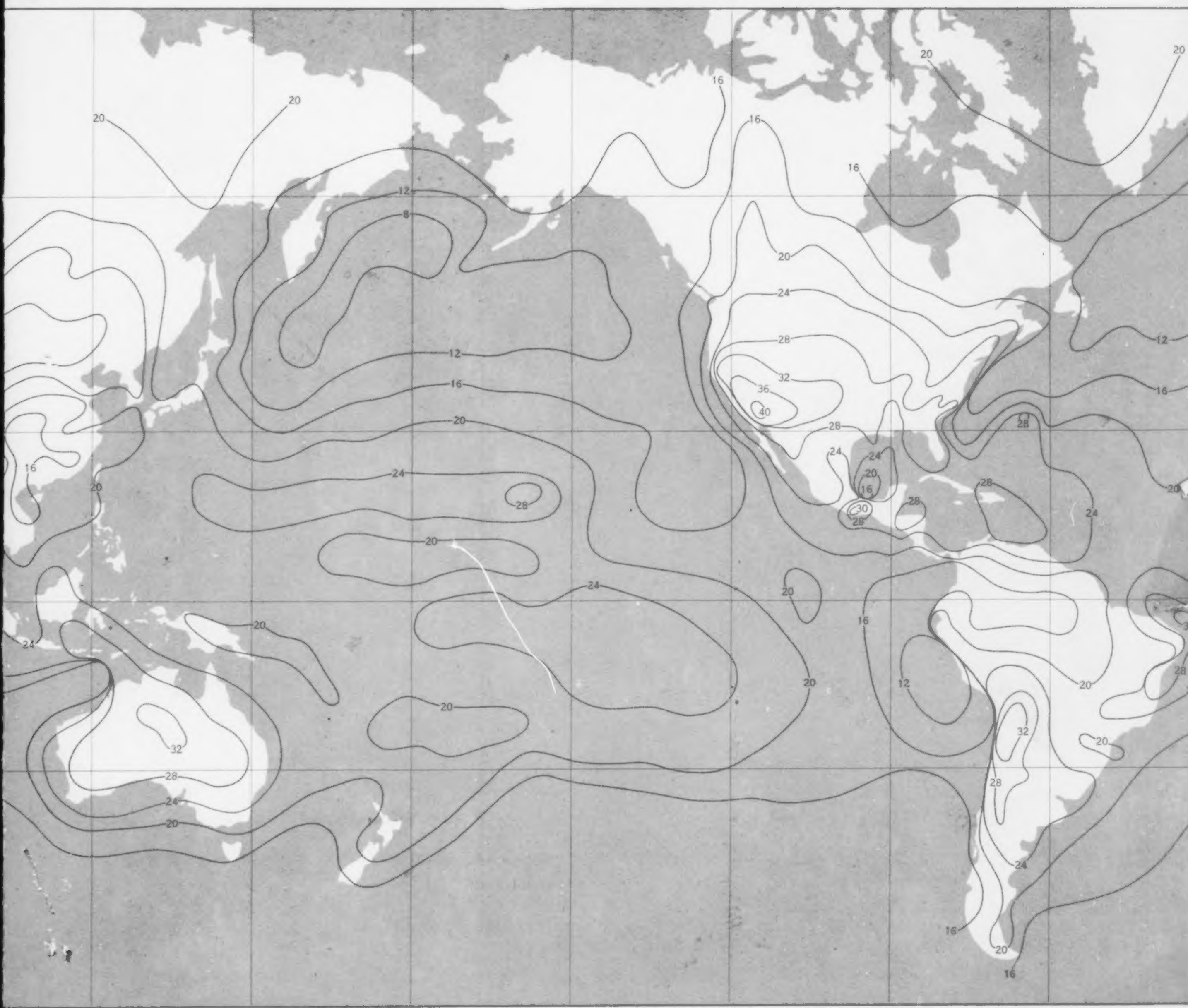
THE JOURNAL OF SOLAR ENERGY SCIENCE AND ENGINEERING

VOLUME I , 1957



THE ASSOCIATION FOR APPLIED SOLAR ENERGY
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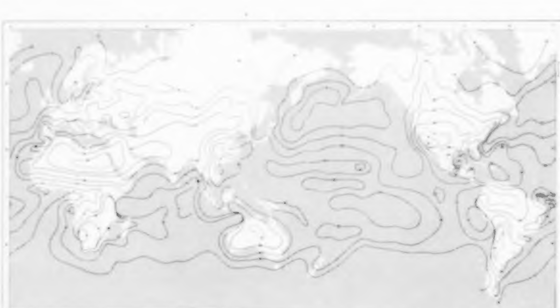

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Held January 21 and 22, 1957, at Phoenix, Arizona

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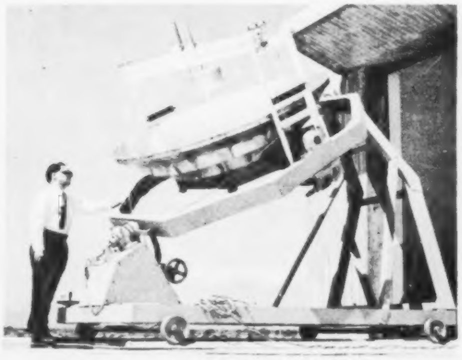

The cover of this issue shows the solar furnace of the Government Industrial Research Institute at Nagoya, Japan. (See paper page 14.) A Conn-type installation constructed in 1955, this furnace uses a 2-m parabolic reflector of high-purity aluminum plate, with no auxiliary mirror.

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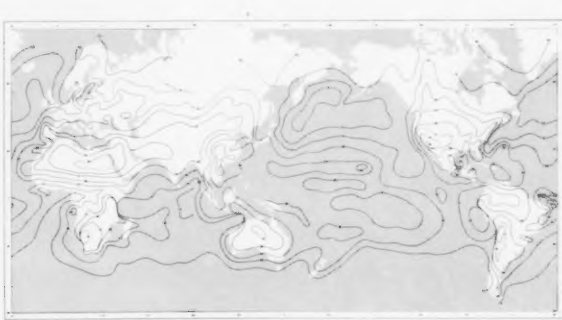

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WEATHER AND SOLAR VARIATION

By C. G. ABBOT, L.L.D.

Research Associate, Smithsonian Institution.

As solar radiation and the weather appear to be affected by identical periods of variation, it is therefore likely that weather changes are produced by solar variation, and can be predicted when the periods are known. Forecasts for precipitation and temperature at St. Louis and Peoria are compared graphically with actual weather data, based on 5-month smoothed running means and extending from 1854 to 1939, as evidence of the author's thesis.

The sun's radiation, which we see and feel, like that of many other stars, is variable. Solar output of radiation seldom exceeds two per cent in its variation. However, its variation comprises as many as 60 regular periodic pulses, ranging from one month or less to 273 months or more. All are exact submultiples (or aliquot parts) of 273 months, as 91, 39, 7 months, and many more. They range in amplitude from 1/50 to 1/4 per cent. All go on simultaneously, like overtones of a musical note.

As many as 30 of these exact periods have been found in weather records which have been kept from 1870 and earlier. They occur in records both of precipitation and temperature. Far from being confined to fractions of one per cent, in precipitation they individually range from 5 to 25 per cent of normal average precipitation. In temperature they range individually from 1° to 5°F. Owing to the large number of these weather periods, some in plus, some in minus phases at any one time, their combined influence is not usually startlingly great.

The natural question rises: If the sun's radiation and the weather are both affected by identical periods of variation, does one produce the other, and can weather be predicted when the periods ar known?

It is certainly not the weather changes that produce the observed changes in the sun's output, as some might think owing to induced errors of observation. For identical results on solar variation are found in series of measures made in Chile with those made simultaneously in Egypt. Furthermore, the variation in measures of solar radiation is correlated with changes in the telescopic view of the sun's surface phenomena, as sunspots, faculae and flocculi.

Meteorologists are very loath to believe that changes of ¼ per cent and less in the solar output of radiation can be the cause of changes of 5 to 25 per cent in precipitation. No theoretical reason can be assigned. But the weather records themselves display to careful examination the changes referred to. No further solar measures are required to testify to the family of periods, identical with solar periods, also revealed in weather. Weather records alone are now sufficient basis to undertake forecasts from these periodic variations.

I have published[1] such forecasts for precipitation at St. Louis, Peoria, Albany, and am now working on Washington and Charleston. I have also published forecasts of temperature at St. Louis and Washington. All of these forecasts, some as much as 60 years from base, show surprisingly good agreement with the actual weather changes.

Before giving graphs which show such correspondences between forecasts and events, I will state several facts which should be kept in mind.

(1) Long records of weather ordinarily give "normal" monthly values found by taking the monthly averages of all the years tabulated. I have found considerable differences in normals, if computed separately for years of high and low sunspot frequencies, respectively. I therefore compute separate monthly normals for years above and below an average of 20 Wolf numbers, in sunspot frequency. From these normals I tabulate the departures in temperature, and the percentages of normal precipitation.

(2) The monthly values have too wide jumps to be most useful. I smooth the record by 5-month consecutive means. Thus for March I use (Jan. + Feb. + Mar. + Apr. + May) × 1/5, and similarly for other months.

(3) As a basis for the forecasts I have made, I use all the monthly data from about 1856 to 1939 inclusive, 1032 months[2]. The average date of basis is about 1897.

(4) Supposing, contrary to meteorologists' opinion, that the variation of the sun is the real cause of the variation of the weather, since it has identically the same periods, I point out that well-known variations of insolation suffer variable lags in their weather influence. Thus solar radiation is a maximum usually at apparent noon, but temperature is highest in most stations several hours later. The lag however differs with locality. Also the sun's radiation is usually a maximum in June, but the temperature reaches a maximum in late July or August at most stations. So the lag differs not only with locality but with length of period.

(5) Lags of solar effects, as they differ with locality, indicate that the state of the atmosphere is an important factor. The atmospheric condition varies not only with locality but with time of the year, prevalence of sunspots, and march of population. To partially meet these difficulties, I tabulate separately for three periods of the year: Jan.-Apr.; May-Aug.; Sept.-Dec.: also with sunspot Wolf numbers, above or below 20: also with lapse of time, before and after the year 1900. These divisions of the available monthly data lead to computing 186 tables, before undertaking a forecast.

(6) Finally, as the atmospheric condition differs with the character and cover of the ground, one cannot predict once and for all at one locality to serve the whole country. One must use many stations for prediction before a network chart can be drawn to indicate the regions of high or low precipitation or temperature.

(7) If I use weather records from 1856 to 1939 as a basis, some may, at first thought, say that between these years no similarity of the curves of forecast and event is an indication of good forecasting. But they should recall that 1032 months have each a part in fixing the form of the curve of forecast for any one year. Its own 12 months can have but 12/1032 influence on the form of that year's curve, or only 1.2 per cent altogether. Even for a 5-year interval, the records of those 5 years have only 6 per cent of influence. So, for all practical purposes, *all* the years for which weather is synthesized by adding the influences of 23 periods are real forecasts, whether before or after 1939.

Additional cautionary or supporting considerations may be found in the papers above cited. I now proceed to display graphs which show the correspondence.

Fig. 1 shows for St. Louis precipitation, for 5 years, 1875-1879, the actual computation of the forecast from a synthesis of 23 periods. The range of precipitation shown is 130 per cent of normal, and the forecast agrees surprisingly well with the event, both in amplitude aad in details.

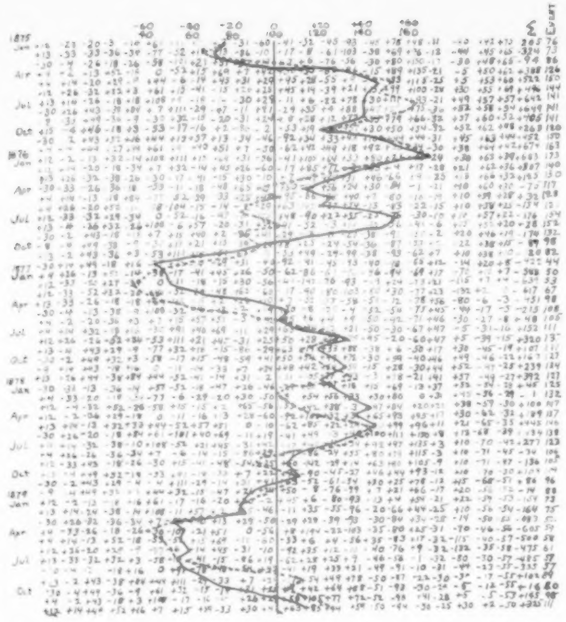


FIG. 1—Facsimile of computation of St. Louis precipitation, 1875-79, compared with the observed precipitation as percentage of normal. Data from monthly mean precipitation smoothed by 5-month running means. Dotted curve from summation of 22 regular periodicities, determined as averages over the 86-year epoch, 1854-1939. Full curve, the event.

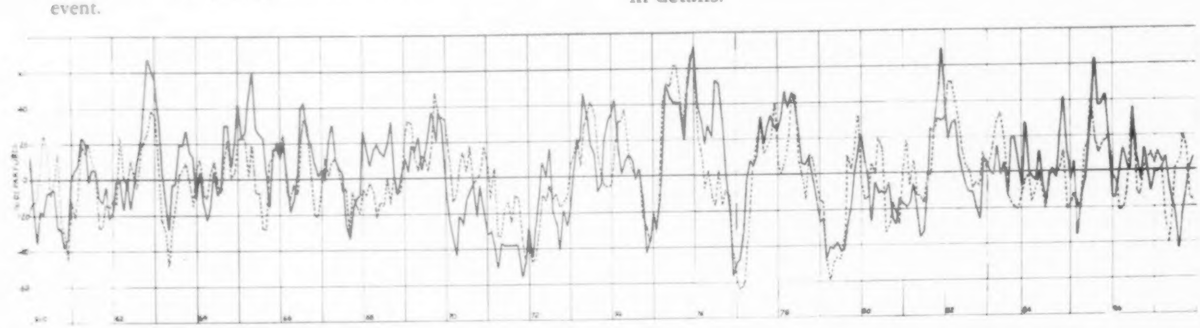
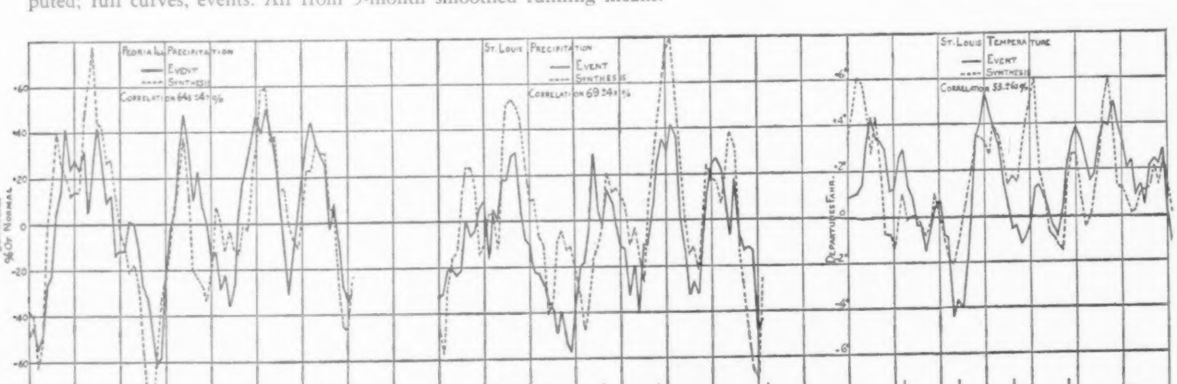


FIG. 2—Synthesis of computations, 1860-1887, of St. Louis precipitation compared to the event. Dotted curve, computed; full curve, the event. All from 5-month smoothed running means.

FIG. 3—Three 6-year predictions 40 years in advance. Precipitation (Peoria and St. Louis) and temperature (St. Louis) computations 1934-39 compared to the events. Precipitation, percentages of normal; temperature, departures from normal. Dotted curves, computed; full curves, events. All from 5-month smoothed running means.



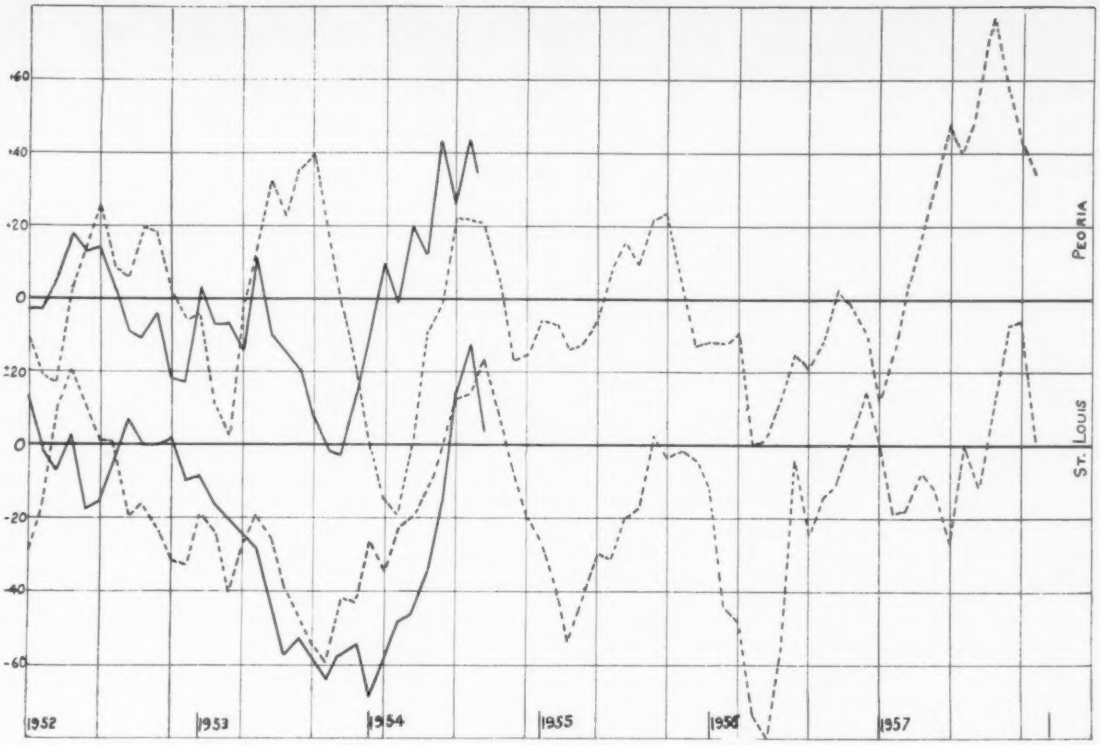


FIG. 4—Predicted precipitation, Peoria (upper) and St. Louis (lower), 1952-57, from mean forms of 22 periodicities over the epoch 1854-1939. End of prediction 18 years after 1939 and 60 years after middle of base, 1897. Dotted curves, prediction; full curves, event. Horizontal lines represent normal precipitation. Drought indicated ending 1957.

Fig. 2 shows for St. Louis precipitation 28 years of comparison between forecast and event, 1860-1887. In general, the two curves are similar, and in the same phase. But after 1884 there are, during several years, several months difference in phases. I show in "Sixty-year Weather Forecasts", above cited, that in 70 years out of 100 there is good agreement, but in 30 years such differences of phase occur. Generally, however, such disagreements seem associated with great volcanic eruptions. Thus in August, 1883, the tremendous explosion of Krakatoa in the Strait of Sunda occurred. It filled the world's atmosphere with dust for several years afterwards.

Fig. 3 gives 5-year comparisons of forecasts and events at St. Louis, Peoria, and Washington.

Fig. 4 is of special interest in relation to drought. Both St. Louis and Peoria forecasts (which, by the way, begin in 1952, 12 years after the end of the basis in 1939) show the beginning, advance, maximum severity in 1956, and probable end in 1957 of the drought in that region.

I cannot but believe, despite the skepticism of official and other professional meteorologists, that the showing I have made, unaided, indicates that it would be worth while to test this method of long range forecasts of seasons (and to a less certainty of months) by computing, for perhaps 30 stations east of the Rockies, the expected precipitation for the seasons, for 10 years in advance. If successful for 70 per cent of the time, and differing only a few months in phases for the other 30 per cent, as at St. Louis, such graphical networks of forecasts for eastern United States might prove of immense worth.

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2. At St. Louis, 1854-1939, 1056 months.

All figures are taken from Abbot, C.G., "Sixty-year weather forecasts", *Smiths.Misc.Coll.*128(3), 1955.

HIGH-POWER SOLAR INSTALLATIONS*

By V. A. BAUM, R. R. APARASI and B. A. GARF

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The results of investigations establishing the possibility of erecting economical solar installations in the sunny regions of the U.S.S.R., to produce 11-13 T**/hr of steam, (p = 30 At, t = 400°C), are presented. The optical system of the installation consists of 1,293 mirrors of 3 x 5 m, mounted on carriages which move on rails, positioned around a boiler-shield, on which the solar rays are focused.

The development of the industrial and commercial utilization of solar radiation must proceed both along the lines of using small solar installations to supply energy to small establishments and of erecting large-scale high-power industrial helio-installations.

The power of a solar installation is proportional to the area of the light-receiving surface. Comparisons of installations of the same type, have shown that the costs of the structure supporting and moving the reflectors and the receptor-absorbers of the radiant energy, and of the structures giving it rigidity, increase at a greater rate than the power of the installation.

Experiment and calculation have shown, for example, that the ratio of the construction costs of the various elements of a parabolic mirror solar installation to the power of the station is proportional to $\left(\frac{D_1}{D_2}\right)^n$, where D_1 and D_2 are the diameters of the parabolic mirrors of two installations being compared, and n is a power between 0 and 1, depending on the type of elements in the installations. As an average for such installations,[1] $n = \frac{1}{2}$ to $\frac{1}{3}$.

A series of investigations completed in the ENIN heliolaboratory of the Russian Academy of Sciences, or under the direction of the associates of the heliolaboratory, has shown that it is difficult to construct a paraboloid solar installation with a movable boiler situated at the focal point of the reflector, with reflector diameters of over 20-25 m, and that such installations are extremely expensive. Therefore the power of an individual solar installation should not be above 130,000 - 250,000 kcal/hr for example, when producing heat, or 40 kwh when producing electricity. The power of individual installations using parabolo-cylindrical mirrors is limited in the same way. Thus the problem of large-scale solar installations remains unsolved.

It is possible to avoid increasing the cost of solar installations when increasing their power by using standard elements in their construction. An interesting arrangement was proposed in 1949 in Moscow by N. V. Lenitski, in which a set of flat mirrors (each of which must be adjusted separately), reflects the light onto an immovable boiler placed above the mirrors. The principal result of this is the development of high-power individual installations. The advantages of the arrangement are that the mirrors are placed close to the ground, and, more important, the increase in power is achieved by the multiplication of standard elements. In order to develop a high power solar installation of satisfactory efficiency, there is a complicating factor: the boiler must be elevated. The distance between the mirrors must be considerable to avoid a high degree of mutual shading when the sun is close to the horizon. At the same time the focal distance of the system must be approximately equal to its diameter, to avoid a low utilization of the mirror surfaces. Therefore the height of the boiler above the mirror surfaces is expressed by the formula:

$$H \doteq \sqrt{\frac{4Q}{\pi E_0 R \phi}}, \qquad [1]$$

where H is the height in meters; Q, the power of the installation in kcal/hr; E_0, the solar radiation in kcal/m²/hr; ϕ, the coefficient of sunlight per unit of mirror area; R, the efficiency of mirror utilization, increasing with the coefficient of mirror utilization.

When $\phi = 0.1$ and the power of the installation is 250,000 kcal/hr, the height of the boiler must be about 80 m. At low latitudes, where the sunlight intensity per unit of the mirror area of the solar installation must be taken as high, the power of the station may be increased proportionately.

An arrangement for such a solar heating station (SHS), with powers up to 10^7 kcal/hr and above, has been developed in the heliolaboratory in the last few years. This is 40-80 times higher than the highest possible power of a single paraboloid installation and 20-40 times the power of an installation using flat mirrors and a stationary boiler lighted from below. The station was designed to produce steam at 30-35 atmospheres. The solar radiation is collected by 19,395 sq m of surface and reflected by 1,293 individual flat reflectors of standard type onto a rotating boiler at the focal point of the optical system formed by the reflectors. Each separate reflecting surface of 15 sq m (3 x 5 m) is composed of 28 mirrors, each assembled on a standard metal frame, situated on a carriage. 1,293 of such carriages are divided into 23 separate trains, which move on concentric rails with equal angular velocity around a boiler situated on a tower 40 m high. Thus the

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*Translation of an article appearing, in Russian, in *Teploenergetika* (Thermal Energy), volume 3, no. 6, pp. 31-39, June, 1956.

**T refers to metric tons.

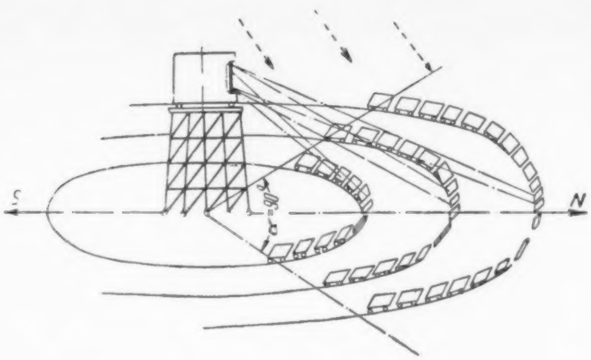


FIG. 1.

mirrors are given azimuthal motion to focus the reflected rays on the boiler. An electrical motor causes the frame to rotate about some nearly horizontal axis to produce the zenithal movement. The arrangement in question is shown in Fig. 1. The zenithal and azimuthal motions are achieved by two respective driving mechanisms.

The angular velocity of the azimuthal rotation must equal the visible angular movement of the sun.

$$\omega_a = \frac{k \cos^2 \delta \,(\sin \phi - \cos kt \tan \delta \cos \phi)}{1 - (\cos \phi \cos \delta \cos kt + \sin \phi \sin \delta)^2}, \qquad [2]$$

where kt is the hourly declension from the meridian, ($k = 15$ if kt is expressed in degrees); δ, the angle of inclination of the sun; ϕ, the latitude of the location.

ω_a, the power delivered by the installation, is at a maximum when $t = 0$ and $\delta = +23° \, 27''$ (June 21, the day of the solstice).

$$\omega_{a\,max} = \frac{k}{\sin \phi - 0.4338 \cos \phi}. \qquad [3]$$

The total power of the azimuthal rotation engine is expressed by the formula:

$$N = 0.0098 \, \frac{\omega_{a\,max}}{\eta} \sum_{1}^{m} n \, [0.7G + \\ + (0.005G + \frac{\overline{S} \rho v^2 F)}{2} \, R] \text{ kw}, \qquad [4]$$

where ω_a is expressed in reciprocal seconds; η is the efficiency of the machine; m is the number of trains; n, the number of carriages in each train; G, the weight of the carriages and reflectors in kg; $\rho = 0.125$ kg sec^2/m^4 is the density of the air; v, the calculated wind velocity in m/sec; F, the reflecting surface in m^2; R, the radius of the train, in meters; $\overline{S}$, the dimensionless wind resistance of the individual carriages:

$$\overline{S} = C_x \cos \psi - C_y \sin \psi + \mu \,(C_x \sin \psi + C_y \cos \psi), \qquad [5]$$

where C_x and C_y are the aerodynamic coefficients determined in a wind tunnel. The relationships $C_x = f(\beta)$ and $C_y = f(\beta)$ for flat plates (where β is the angle of incidence) may be seen from Fig. 2, which was plotted from the experimental results of a series of investigators.[2] The action of aerodynamic force on the reflectors is shown in Fig. 3:

$$\beta = 90 - \left(\gamma + \frac{\alpha}{2}\right), \qquad [6]$$

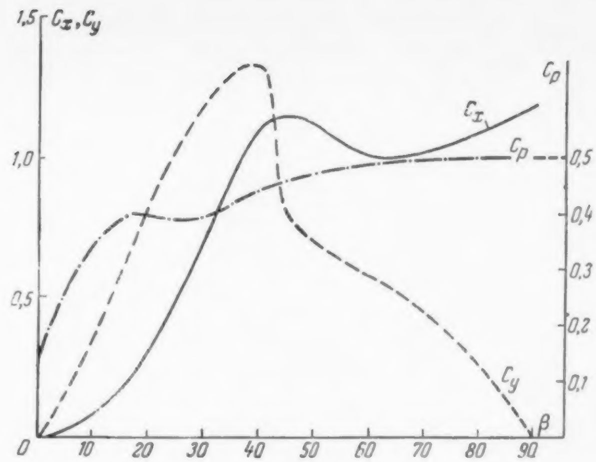


FIG. 2—Aerodynamic characteristics of reflectors.

γ is the angle between the wind direction and the axis of symmetry of the system; α, the angle between the axis of symmetry of the system and the radius, determined for the reflector in question:

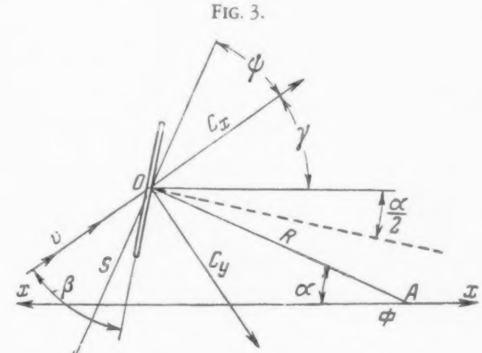
$$\psi = \beta - \frac{\alpha}{2}; \qquad [7]$$

μ is the coefficient of sliding friction, equal to 0.15.

The power of the motor is determined from the most unfavorable wind direction [angle γ in formula (6)], and the maximum wind velocity V. Calculations carried out in the heliolaboratory have shown that when $V = 10$ m/sec, a satisfactory value is obtained for N_{max}, that is, about 2.5 per cent of the electrical power of the station. However, the average value, derived from formula (4), is substantially below the maximum; thus $\overline{S_{av.}} = 0.142$ while $\overline{S_{max}} = 0.228$. The average wind velocity for most regions of central Asia may be taken as 4-5 m/sec, etc. Therefore the average power necessary for the azimuthal rotation of the optical system of the station may be established as not larger than 0.7 per cent of the power of the station.

The *zenithal rotation* is accomplished separately for each individual reflector. Depending on the angular height h of the sun, each reflector must be turned so that its optical axis (normal to the reflecting surface) defines the

FIG. 3.



angle z with the horizontal plane, and the angle between the projection of this normal on the surface and the axis of symmetry of the station has the value ϑ. These angles must satisfy the formulas:

$$\tan \vartheta = \frac{\sin a \cos \theta}{\cos a \cos \theta + \cos b} \qquad [8]$$

$$\tan z = \cos \vartheta \frac{\sin b + \sin \theta}{\cos a \cos \theta + \cos b} \qquad [9]$$

where θ is the angle between the reflected light and the horizontal plane, for which $\tan \theta = H/R$, where H is the elevation of the boiler.

Thus each reflector rotates about two axes, one horizontal and one vertical. However, investigations carried out in the heliolaboratory have shown that in practice the mirror may rotate about a single inclined axis, different for each reflector. In this case the normals do not deviate from the true direction by more than 1′ 15″. The position of this axis, defined by its angles μ, ν and η with the coordinate axes, may be found from the solution of the four-equation system:

$$\left.\begin{aligned} &\cos z_1 \cos \vartheta_1 \cos \mu + \sin z_1 \cos \nu + \\ &+ \cos z_1 \sin \vartheta_1 \cos \eta = \cos \phi; \\ &\cos z_2 \cos \vartheta_2 \cos \mu + \sin z_2 \cos \nu + \\ &+ \cos z_2 \sin \vartheta_2 \cos \eta = \cos \phi; \\ &\cos z_3 \cos \vartheta_3 \cos \mu + \sin z_3 \cos \nu + \\ &+ \cos z_3 \sin \vartheta_3 \cos \eta = \cos \phi; \\ &\cos^2 \mu + \cos^2 \nu + \cos^2 \eta = 1 \end{aligned}\right\} \qquad [10]$$

where z and ϑ are defined by formulas (8) and (9) for three separate heights of the sun. At the same time θ is defined as the angle between the normal to the reflctor and the unknown axis of rotation. The reflector must rotate with some change in angular velocity.

$$\frac{d\psi}{dt} = - \frac{dz}{dt} \frac{\cos z}{\sqrt{\sin^2 \phi \sin^2 \nu - (\sin z - \cos \theta \cos \nu)^2}} \qquad [11]$$

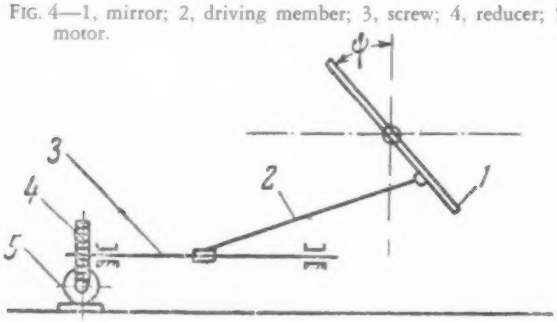
where z, and therefore dz/dt may be found from formulas (8) and (9).

The transference number i of the mechanism is defined on the basis of the maximum value of $d\psi/dt$. The total transference number of the mechanism

$$i = 0.1045 \frac{n_m}{\left(\frac{d\psi}{dt}\right)_{max}}, \qquad [11a]$$

where n_m is the revolutions per minute of the motor; and $d\psi/dt$ is expressed in reciprocal seconds.

FIG. 4—1, mirror; 2, driving member; 3, screw; 4, reducer; 5, motor.



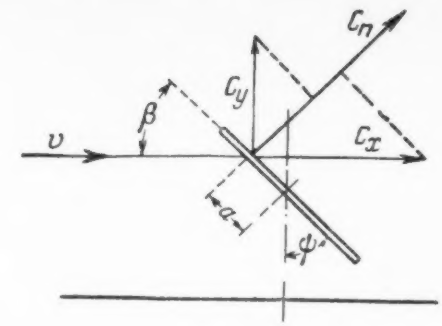


FIG. 5.

The turning mechanism for the mirrors may be provided with a hydraulic drive or an electric motor with a reducer. The latter is simpler. A kinematic arrangement, as shown in Fig. 4, was adopted for the project outlined by the SHS. In determining the forces acting on the reflector and the power necessary for zenithal rotation, it must be kept in mind that due to the equilibrium of the reflector, all forces but the aerodynamic ones may be neglected (Fig. 5).

The aerodynamic moment

$$M = C_n \frac{\rho v^2}{2} \cdot Fa. \qquad [12]$$

where C_n is $C_x \sin \beta + C_y \cos \beta$.

The aerodynamic moment

$$a = \frac{t}{2} (1 - C_p), \qquad [13]$$

where t is the chord (height of the reflector). The relationship $C_p = f(\beta)$ was introduced earlier in Fig. 2.

According to the calculations performed, the maximum value for the aerodynamic moment may be calculated from the formula:

$$M_{max} \doteq 0.01\, v^2 Ft \qquad [14]$$

Then the maximum power necessary for an individual motor

$$N_{1\,max} = \frac{0.01\, v^2 Ft}{\eta} \left(\frac{d\psi}{dt}\right)_{max} \qquad [15]$$

Numerical calculations show that N_{max} is not more than 3-5 watts. 50 watt motors were used in the project.

Since $d\psi/dt$ varies with time, the central rotating mechanism must be provided with an automatic machine with a following mechanism, engaging the drive when a beam reflected from the center of the mirror deviates from the focal center of the boiler opening.

The optical quality of the system of mirrors in the installation is high enough to assure a high coefficient of utilization of the radiant energy of the sun for the given purpose. However, such an arrangement is possible only by the use of automatic machinery to focus the reflectors with the aid of simple mechanisms. The average value of the angle between the incident and reflected light is com-

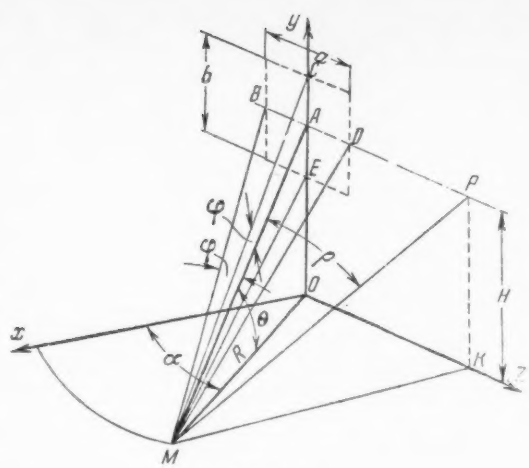


FIG. 6.

paratively small, and therefore the coefficient of utilization of the mirror surface is high, up to 0.93. The concentrating capacity of this system is higher than that of an individual parabolo-cylindrical mirror but lower than that of a paraboloidal one. The average geometric concentration obtained is around 150, which is sufficient for the economic production of steam at 30-35 atmospheres.

The actual conditions of light reflections from flat mirror elements are different from the ideal ones. The sun does not act as a point source of radiant energy, so that the rays, even reflected from ideal mirrors, diverge from points by the angle $2\phi_0 = 32'$, equal to the angular diameter of the sun. Inaccuracies in the mirror (unevenness of the surface, unsatisfactory polish), increase the deviation. In practice a polished-glass mirror may be assumed to have a total ray deviation of:

$$2\,\phi = 1^\circ.$$

The dimensions of the focal spot (Fig. 6), projected on the heating surface of the boiler, may be defined by the formulas:

$$a = 2\,R\,\sqrt{\tan^2\theta + \cos^2\alpha}\cdot\frac{\sin 2\phi}{\cos 2\,\rho + \cos 2\,\phi} + \frac{a_0 \cos\omega}{\cos\rho}\,; \qquad [16]$$

$$b = \frac{2\,R \sin 2\,\phi}{\cos 2\,\theta + \cos 2\,\rho} + \frac{b_0 \cos\omega}{\cos\theta}\,; \qquad [17]$$

$$\rho = \text{arc cos}\,(\cos\theta\sqrt{\tan^2\theta + \cos^2\alpha,}\ ) \qquad [18]$$

where a_0 is the width of the reflector; b, the height of the reflector; $\cos\omega$, the coefficient of utilization of the mirror surface $= 0.93$; for the value of θ see formula (8); the maximum values of R and α must be used in the calculations.

Various factors may lead to some displacement of the focal image from the focal opening of the boiler during the operation of the station. This may involve an individual reflector or a small number of them. Some such causes are: deformation of the reflector housing by aerodynamic stress, unevenness in the setting-up of the railway, a slack between the rails and the wheel rims, etc.

This displacement may be corrected by installing an automatic mechanism of zenithal rotation (for example, by placing the rails at various heights). The displacement of the focal image due to slack between the wheels and rails may be defined by the formula

$$\Delta\,a = \frac{2\,R\,\Delta\,S}{l_m \cos\alpha}, \qquad [19]$$

where ΔS is the possible slack; l_m, the distance between the carriage axles.

To decrease the possible deformation, especially the twisting, the mirror framework must be filled with strong spatial ribs. Calculations made in the heliolaboratory show that the possible deviation due to so-called "accidental" causes is small, and has no real effect on the optical characteristics of the station as a whole.

The distribution of energy on the focal spot of the solar boiler may be determined on the basis of the theoretical and experimental work of the associates of the heliolaboratory.

A formula which describes the thermal intensity at each point of the focal spot in relation to its distance from the center has the form (3):

$$E = 8.36\cdot 10^3\,E_0\,R_3\,A_{max}\,b^2 \times$$
$$\times \exp.\left\{-3.283\cdot 10^3\left(\frac{rb}{p}\right)^2(1+\cos u_{max})^2\right\}, \qquad [20]$$

where E_0 is direct solar radiation; R_3, the reflection coefficient of the mirror; A_{max} is a geometric function:

$$A_{max} = \frac{\pi}{2}\left\{\frac{\sqrt{2}}{3}\,(2-\cos u_{max})\times\right.$$
$$\left.\times\sqrt{1+\cos u_{max}} - \frac{2}{3}\right\}; \qquad [21]$$

u_{max} is the maximum angle of girth of the system; b, a measure of accuracy ($b = 1$ in our calculations); p, twice the distance from the focus to the nearest reflector; r, the distance from the center of the focal spot in the focal plane.

The results of computations conducted in SHS are plotted in Fig. 7. The area of the focal spot is divided in Fig. 7 into nine oval rings, and the average thermal intensity for each is given.

The method used in calculating the optical sections was based on geometric formulations. The problem of experimental verification arises in this connection. A model station was erected for the purpose in a ratio of 1:50, with 5 trains of mirrors. The reflectors of the model consisted of metal plates each with 8 flat mirror elements, 50 x 50 mm, glued onto it; each reflector surface was equal to 100 x 200 mm. There were 66 such reflectors. Making the mirror elements in a ratio of 1:50 was unsatisfactory due to the excessively small dimensions of elements. The increase in size of the mirror elements caused a small enlargement of the focal spot.

The energy of the focal surface and the time required to

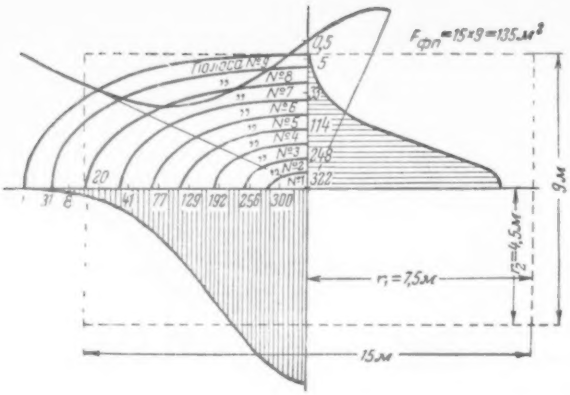


FIG. 7—Graph showing distribution of the energy absorbed by the boiler placed at the focal plane of the SHS, in thousands of kcal/m² hr.

bring 1.25 liters of water to the boiling-point were measured using a horizontal calorimeter 300 x 250 x 100 mm in dimensions in place of the boiler.

The energy of the focal surface was determined by a method elaborated in other solar establishments with concentrating arrangements. The calorimeter was operated at a temperature only slightly different from that of the air, allowing us to neglect the convection and radiation losses of the calorimeter. The heating surface of the calorimeter was whitened with chalk dust at the beginning and then gradually blackened with mineral soot, passing out from the center in concentric circles. The coefficients of blackness were taken as $\epsilon_b = 0.92$ and $\epsilon_w = 0.18$ for the black and white surfaces respectively.

The heat increment ΔQ_{incr} was measured after each complete blackening of the surface, and this was divided by the increased blackened area ΔF and the difference $\epsilon_b - \epsilon_w$. The results of calculation gave a thermal intensity of the surface equal to:

$$E = \frac{\Delta Q_{\text{incr}}}{\Delta F\,(\epsilon_b - \epsilon_w)} \qquad [22]$$

The experimental points and the defining curve E, calculated from the theoretical formula, are shown in Fig. 8. The efficiency of the model (in spite of the inaccuracies in its preparation) was obtained as 0.44 for a total reflecting surface $F_{\text{tot}} = 66 \cdot 0.02 = 1.32$ m², which is sufficiently close to the calculated value. This shows the reliability of the theoretical formula adopted for the development of the SHS installations.

The heat loss, heat production, and efficiency may be determined using the usual methods of determining thermal intensity or the coefficient of concentration of solar radiation in the area of the focal spot of the mirror system of the station.

The following system of equations was solved for the individual ring parts:

(1) Heat produced in heating and vaporizing water or superheating steam

$$Q_{\text{incr}} = G\,[(t_{p1} - t_{p2})\,C + q];$$

(2) Heat transmitted through the boiler walls

$$Q_{\text{incr}} = \frac{t_{\text{surf}} - t_p}{\Sigma\frac{\delta}{\lambda} + \frac{1}{a}}\,F;$$

(3) In the calculation of the radiant solar energy absorbed by the boiler surfaces

$$Q_{\text{abs}} = E_o\,KR\,(1 - A_{\text{dust}})\,\epsilon F;$$

(4) The relation between the solar radiation received and Q_{abs}:

$$Q_{\text{abs}} = E_o\,R\,(1 - A_{\text{dust}})\,\epsilon\,F_3\,\eta_3;$$

(5) To define the heat lost from the surface of the boiler by convection, radiation, and through the insulation:

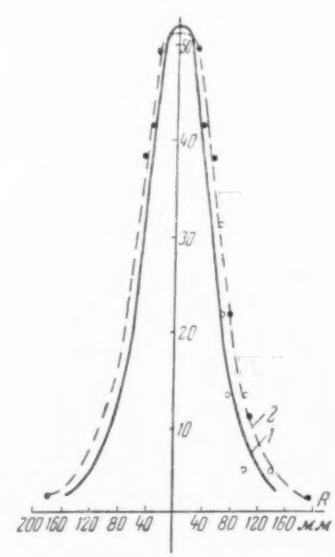
$$Q_{\text{lost}} = [(a_{\text{conv}} + a_{\text{rad}})\,(t_{\text{surf}} - t_{\text{at}}) + k\,(t_p - t_{\text{at}})]\,F;$$

(6) Heat balance:

$$Q_{\text{incr}} = Q_{\text{abs}} - Q_{\text{lost}}$$

Here G is the amount of of steam produced, and t_{p2}, t_p, t_{surf} and t_{at} are the temperatures respectively of the boiler material at the beginning and end of the heating period, of the surface of the boiler elements, and of the surrounding media. $\Sigma\frac{\delta}{\lambda}$ is the sum of the thermal resistance to heat conduction; k is the coefficient of thermal conductivity through the boiler wall, and a is the thermal efficiency; E_o is the solar radiation, K the geometric coefficient of radiation concentration; R is the coefficient of reflection of the mirrors of the station; ϵ is the degree of the blackness of the surface; A_{dust} is a coefficient for calculating the radiation absorbed by the dust on the mirrors; η_3 is the coefficient of utilization of the mirror sur-

FIG. 8—Distribution of the energy in the focal plane of the SHS model: 1, theoretical curve; 2, from experimental data.



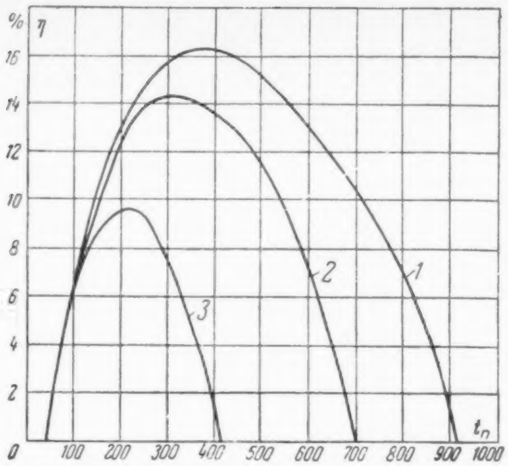


FIG. 9—Coefficient of useful power from the transformation of solar radiation into electrical energy in solar steam-powered stations in relation to the temperature of the steam: 1, station with mirrors giving a concentration $K = 200$; 2, station with mirrors giving a concentration $K = 100$; 3, station with mirrors giving a concentration $K = 30$.

face (the rays strike the mirrors at a small angle from the perpendicular).

When the light is concentrated, as this arrangement provides, in the area of the focal spot, it is convenient to make the boiler in the shape of a tubular shield, lighted by the radiation on one side and insulated on the other.

The temperature and pressure of the superheated steam are chosen in relation to the concentration of radiation so that the efficiency of the solar station as a whole will be at a maximum. When the steam parameter is raised, the thermodynamic efficiency of the power installation is increased, but the heat losses from the boiler surface by convection and radiation are also increased.

The results of calculations of the relationship between the overall efficiency of the solar installation and the light concentration and the steam temperature are shown in Fig. 9. Approximate calculations were made for several average values of light concentration and boiler surface temperature. The following steam parameters were adopted for the solar steam boiler on the basis of the calculations: pressure (30-35) At, superheating temperature (375 - 400) °C.

In the calculations, η_3 was taken as 0.93, $R = 0.8$, $\epsilon = 0.9$, $E_o = 700$ kcal/m^2/hr, $A_{dust} = 0.03$.

It was approximately determined from a series of investigations that the quantity of heat practically utilized in the steam-boiler to produce steam, $Q_{useful} = 8{,}260{,}000$ kcal/hr. with $p = 35$ At., $t = (375 - 400)$°C, the productivity of the boiler was

$$D_{400} = 11{,}000 \text{ kg/hr}.$$

A *waste-gas heater,* whose heating surface is close to the periphery of the focal spot, heats the water from 30 to 200-240°C. The heat absorbed is

$$Q_{wgh} \doteqdot \Delta i\, D = 2{,}400{,}000 \text{ kcal/hr}.$$

The heated area of the waste-gas heater should be around 104 sq m. The heat lost from the open surface of the waste-gas heater by radiation and convection, calculated from its various parts, and through the insulation, is equal to 215,000 + 14,000 $\doteqdot$ 230,000 kcal/hr.

The superheater, in which the steam is superheated up to 375 — 400°C, may not, as shown by calculations, be placed in the central part of the focal spot, which would greatly over-heat the cylinder wall due to the high thermal intensity in the zone. The surface of the steam superheater is located in a zone containing part of ring No. 5, 5.2 sq m in area, and part of ring No. 4, 5.5 sq m in area. The total area is 10.7 sq m. About

$$Q_{sup} = \Delta i_{sup}\, D = 1{,}1200{,}000 \text{ kcal/hr}.$$

is used to superheat the steam. The heat lost from the superheater by radiation and convection and through the insulation is equal to 160,000 + 4,000 = 164,000 kcal/hr. The temperature of the superheater walls will vary from 380°C at the entrance of the steam up to 504°C as it leaves.

The vaporizing section is located in rings No. 1, 2, 3 and parts of 4, of the focal spot. The total area of the vaporizer is 20.7 sq m. The heat absorbed by the vaporization at 240° is 4,600,000 kcal/hr. The heat loss from the open and insulated parts of the vaporizer is equal to 140,000 + 5,000 = 145,000 kcal/hr.

The distribution of thermal intensity in the various rings of the focal spot, and the energy absorbed by the water and steam across the boiler surface of the focal spot, are given in the table:

Ring no.	Ring area in sq m	Thermal stress in thousands of kcal/sq m/hr	Energy in thousands of kcal/hr	Ring parts
1	2.4	335	805	vaporizer
2	5.0	283	1,420	$F = 20.7$ m^2
3	7.9	216	1,700	vaporization at
4	5.4		820	$p = 35$ At.
		151		superheater,
				$F = 10.7$ m^2,
	5.5		830	superheating
5	5.2		490	from 240°C to
		94		(375 - 400) °C
	10.0		940	
6	18.9	48	920	waste gas heater
7	22.2	25	540	$F = 103.6$ m^2,
8	27.3	9.0	247	heating water
9	25.2	2.7	68	from 30 to 240°C
Total	135		8,780	

Thus the useful heat from the waste-gas heater, vaporizer and superheater of the boiler is

$$Q_{use} = 8.20 \times 10^6 \text{ kcal/hr}.$$

The heat loss from these parts of the boiler is $5.4 \times \times 10^5$ kcal/hr. The coefficient of useful work for the station, defined as the ratio of the heat contained in the steam ($p = 35$ At, $t = 400$°C) to the amount of radiant solar energy falling on the mirrors, is equal to:

$$\eta_{stn} = \frac{E_o F_3 R \epsilon \eta_3 (1 - A_{dust}) - 5.4 \cdot 10^5}{E_o F_3 \eta_3}$$

$$= \frac{8.13 \cdot 100}{12.56} = 64.7\%$$

For regions whose solar climate is similar to that of Tashkent, where the incidence of solar radiation on a surface perpendicular to the rays is around $1.7 \cdot 10^6$

kcal/m² year, the productivity of a station whose steam parameters are 35 At and 400°C, may be around

$$D = \frac{\sigma F_3 \eta_3 \eta_{stn}}{i_{steam}} = \frac{1.7 \cdot 10^6 \cdot 19{,}300 \cdot 0.93 \cdot 0.647}{770 \cdot 1{,}000}$$
$$= 25{,}700 \text{ T/year.}$$

Taking into account that the station cannot operate on days of fluctuating weather, and calculating the heat losses on warming the installation to start it up, the productivity of the station may be taken as 20,000 T of steam per year.

The mirror arrangement described, which permits the achievement of substantial amounts of geometric concentration of radiation, 150-200 times, may also be used in the construction of high-power thermoelectric generators. The solar radiation is not collected in this case on the surface of a steam boiler, but on a surface of the same area formed by the hot junctions of a thermoelectric battery which transforms the heat it receives from the solar radiation into electrical energy.

Assuming that the temperature of the heated junctions of the thermoelectric generator $t = 400°C$, with a generator efficiency of 7 per cent, the overall efficiency of the thermoelectric generator may be around 4 - 4.5 per cent for a solar radiation $E_0 = 700$ kcal/m² hr.

The economics of solar heating stations can only be estimated at present. The price of a megacalorie produced by the station was taken as the basic economic criterion in the calculations. The amortization and operating expenses were included in the cost of the heat produced. The latter is the total of the wages of the attending personnel, the upkeep, and the cost of the electricity used by the station for its own requirements.

The capital outlay for construction is used to calculate the amortization costs. The cost of a small series of stations was used rather than of single experimental sample stations, which are doubtless much more expensive. The amortization periods of the various parts of the construction are calculated from the operation of analogous constructions. In regard to the maintenance staff, it is taken into account that the removal of dust from the mirrors may be mechanized. The net cost of cleaning-up per megacalorie of heat produced by a solar station, in relation to the mirror area F of the station, is shown in Fig. 10.

For comparison, the cost of a megacalorie of heat produced by steam boilers heated by coal, K_{fuel}, depends upon the cost of fuel at a given locality, p rubles/T fuel. K_{fuel} was determined according to the following formula:[4]

$$K_{fuel} = (2.25 + 2.21 \frac{p}{100})\ 10.$$

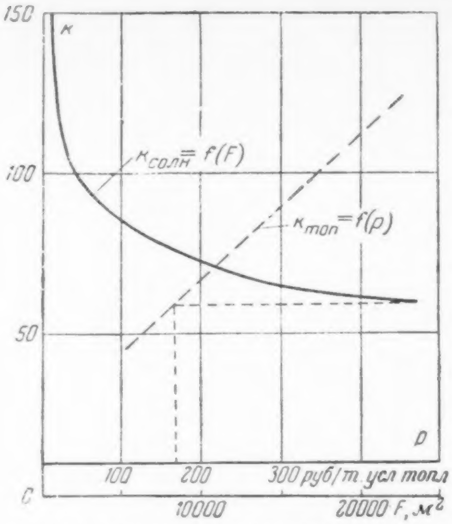


FIG. 10—Net cost of production for SHS of different powers.

Comparison of the curves $K_{solar} = (F)$ and $K_{fuel} = f(p)$, permits the determination of the price using a conventional heating-chamber at which a solar station of this or a different power begins to be more economical than a fuel-powered station. The net cost of the heat produced by a solar station falls as the power of the station increases (Fig. 10). However, this decrease is not very sharp in the range $F = 10{,}000 - 25{,}000$ sq m.

Thus in some cases, when the requirements are quite small, it may be economical to construct low-power solar stations of the type described. When a ton of conventional fuel costs 170 rubles or more, solar stations with mirror surfaces of 25,000 sq m are more economical than fuel-powered stations. Such fuel prices occur in many regions of central Asian republics 100-200 km from a rail system.

In such areas it is economical to use solar energy with the aid of the station described, for such purposes as lifting and delivering irrigation water, heating in winter and cooling rooms in summer, cooling storehouses, producing ice, and distilling salt water. Also, solar electric stations may work in conjunction with hydroelectric or fuel-powered electric stations.

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SOLAR RADIATION AVAILABILITY ON SURFACES IN THE UNITED STATES AS AFFECTED BY SEASON, ORIENTATION, LATITUDE, ALTITUDE AND CLOUDINESS*

By CLARENCE F. BECKER and JAMES S. BOYD**

This paper presents a method for estimating the quantity of solar radiation available on surfaces with various orientations in the United States. Seasonal curves show the availability of solar radiation during cloudless days on surfaces with various orientations at or near sea level. Polynomials have been developed for curves of the horizontal surface. The ratios of solar radiation incident upon tilted surfaces to that incident on horizontal surfaces are presented in the form of curves for which polynomials have been developed. Curves and polynomials giving the percentage increase in solar radiation with altitude are shown; these curves and polynomials can be used to correct the values for conditions at or near sea level. A regression equation correlates the ratio of recorded to calculated cloudless day radiation and cloudiness. Comparisons are shown between the calculated cloudless day radiation determined from the curves and polynomials and recorded clear day radiation.

Radiation from the sun is essentially the primary source of all energy used by mankind. Energy supplies that are most easily utilized, such as the fossil fuels, have undergone natural concentration. The life expectancy of fossil fuel reserves is difficult to determine with accuracy, for it involves not only the uncertainty of estimates of the quantity of fuel present, but also the prediction of rates of production and of demand. In addition, there are coal, oil, and gas in the earth's crust that may never be used because it would not pay to dig to the depths necessary to recover them. The finding of large deposits of uranium in recent years will alleviate the energy situation. This type of fuel, like fossil fuels, cannot be considered inexhaustible as plant size, waste disposal, and distribution of energy tend to raise the cost.

It is evident that the earth's supply of fuels — wood, gas, oil, and coal — is limited and that severe shortages of this form of energy are possible within a century. There is need to learn how to use the daily supply of energy from the sun directly before the stockpile of other energies is exhausted.

Solar energy is immense in quantity but relatively low in intensity. Because of the vastness of the supply of solar energy, the direct conversion of solar radiation into useful forms of energy has great attractiveness. Solar radiation is currently being used on a limited basis for distillation of salt water, for manufacture of salt by solar evaporation, for water heating in southern United States, and for generation of electricity by thermopiles, by the photogalvanic effect, or by the solar battery utilizing a silicon p-n junction. Work is being done in photosynthesis in an attempt to shorten the time necessary for completion of the process by which petroleum was naturally formed.

The utilization of solar energy by the above-mentioned methods is still very inefficient. However, the direct collection of solar energy as heat is much more efficient and the greatest progress is likely to take place in this direction in the near future. Experimental solar collectors for heating air have been built by Buelow,[3] Lof,[12] Telkes[15] and others, and a collector for heating water has been built by Hottel.[7] These collectors have efficiencies as high as 50 to 80 per cent. The possibility of utilizing solar energy on the farm for such uses as final drying of grain, hay, and other crops and to provide supplemental heat to farm buildings is also good.

To utilize solar energy at the surface of the earth for engineering application, it is necessary to determine the availability of the supply. It is the purpose of this paper to show curves and equations useful for estimating quickly the quantity of solar-radiation energy available on surfaces with various orientations anywhere in the United States.

SOLAR ENERGY BEYOND THE ATMOSPHERE

The solar constant is the energy incident upon a unit area located at mean distance of the earth from the sun and oriented perpendicular to the sun's ray beyond the atmosphere. The most recent data available for the value of the solar constant are presented by Johnson.[9] His value is 2.00 $\pm$ 0.04 calories per minute per sq cm or about 440 btu per sq ft per hour.

The spectral distribution of solar energy outside the atmosphere is such that for all practical purposes, the energy lies between the limits of 0.22 and 7 microns. About 0.14 per cent of the energy has wave length greater than 7 microns and 0.02 per cent of it has wave length less than 0.22 microns.

* Based on a Ph.D. Thesis prepared by the senior author while on leave from the University of Wyoming, for the Dept. of Agricultural Engineering, Michigan State University. Approved as journal article No. 1978 by the Michigan Agricultural Experiment Station.

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INTENSITY OF SOLAR RADIATION UPON SURFACES LOCATED AT THE SURFACE OF THE EARTH DURING CLOUDLESS DAYS

Direct Radiation Incident upon a Surface Perpendicular to the Sun's Rays

In tracing the solar spectrum down through the atmosphere during cloudless days, depletion of the direct beam takes place by scattering and absorption.[4, 11] Scattering is caused primarily by air molecules, dust, and to a certain extent by water vapor along the path of the sun's rays to the surface of the earth. The principal absorbing agents are water vapor, ozone and cloud particles.

In a very important paper, Moon[13] has calculated the direct solar radiation incident upon a surface normal to the sun's rays during cloudless days. His calculations of the spectral distribution of the energy at sea level are based on an assumed atmospheric condition of 2 cm of precipitable water vapor, 300 dust particles per cc, and 0.28 cm of ozone at 760 mm of mercury pressure and 0°C.

Moon's data have been taken as standard for cloudless-day summer conditions by the American Society of Heating and Ventilating Engineers. The integrated direct solar radiation as a function of the solar altitude appears in the *Heating, Ventilating, and Air Conditioning Guide.*[1]

F. W. Hutchinson and W. P. Chapman[8] have applied Moon's calculations to a standard winter atmosphere with assumed atmospheric conditions of 33° F dew point, 300 dust particles per cc, and 0.28 cm of ozone.

Solar Angles

The angle at which the sun's rays reach a surface on the earth changes from day to day and from hour to hour owing to the changing position of the earth relative to the sun and to the rotation of the earth about its axis. The sun as seen by an observer on the surface of the earth follows a circular arc from horizon to horizon. This position can be defined by the solar altitude b and the solar azimuth a. These angles vary continuously from sunrise to sunset and are different for each day of the year. The diurnal variation is symmetrical with respect to a north-south line and, therefore, with respect to solar noon.

The sun's altitude and azimuth can be secured from the United States Hydrographic Office Tables 214[17] if the latitude, local hour angle, and declination of the sun are known. The declination of the sun can be secured from any table of ephemeris. The local hour angle is expressed in degrees using 0° for solar noon, 15° for 11 a.m. and 1 p.m., 30° for 10 a.m. and 2 p.m., etc.

Angle of Incidence for Direct Radiation

A formula for determining the angle of incidence of direct solar radiation upon a surface is given by Brown and Marco;[2] their formula was changed to the following form by trigonometric substitution:

$$\cos i = \sin b \sin e + \cos b \cos a \cos e \qquad [a]$$

where i is the angle of incidence; a, the wall solar azimuth; b, the solar altitude; e, the angular tilt of surface from vertical.

For a horizontal surface, e in equation (a) is 90 degrees and the equation becomes:

$$\cos i = \sin b \qquad [b]$$

For a south-facing vertical surface, e in equation (a) is 0° and the equation becomes:

$$\cos i = \cos b \cos a \qquad [c]$$

Then:

$$I = I_o \cos i \qquad [d]$$

where I is the direct solar radiation incident upon a surface; I_o, the direct solar radiation incident upon a surface normal to the sun's rays.

SKY RADIATION

As the solar radiation passes through the atmosphere to the surface of the earth, the depletion of the direct solar radiation is due partially to scattering. A portion of the scattered radiation will return to space, but some of it will reach the surface of the earth as sky radiation.

According to Fritz[4] the diffuse sky radiation on a horizontal surface for an average clear sky is about 16 per cent of the total when the sun is high in the sky and about 37 per cent of the total when the solar elevation is about 10°.

The theory of radiation scattering is rather involved and at this time no theoretical method for calculating the quantity of sky radiation is known. Several investigators have measured sky radiation separately from the direct radiation. Klein[11] gives a method for computing sky radiation in terms of atmospheric conditions, and Hand[6] has published information on the ratio of direct-to-sky radiation during typical winter cloudless days for horizontal surfaces.

Possibly the best information on sky-radiation availability at this time has been presented by Parmelee.[14] He has measured and plotted sky solar radiation versus direct solar radiation for a horizontal surface, and sky radiation versus solar altitude and wall solar azimuth of the vertical surface.

TOTAL SOLAR RADIATION

The total solar radiation during cloudless days incident upon a surface is found by adding the direct and the sky radiation upon the surface.

DAILY TOTAL SOLAR RADIATION AVAILABLE AT THE SURFACE OF THE EARTH DURING CLOUDLESS DAYS

Procedure for Calculating Hourly Rates

The calculation of hourly rates of direct and sky radiation was carried out for the 21st of each month using the following procedure:

(1) The solar declination was secured for the 21st of each month from the ephemeris.[18]

(2) With the solar declination known, the solar altitude and solar azimuth were secured for each daylight hour of the day at 30°, 35° 40°, and 45° north latitude from the United States Hydrographic Office Tables Number 214.[17]

(3) With the solar altitude for each hour known, the direct solar radiation at normal incidence (I_o) was secured from the curve presented by Hutchinson and Chapman[8] for the months of September through March and

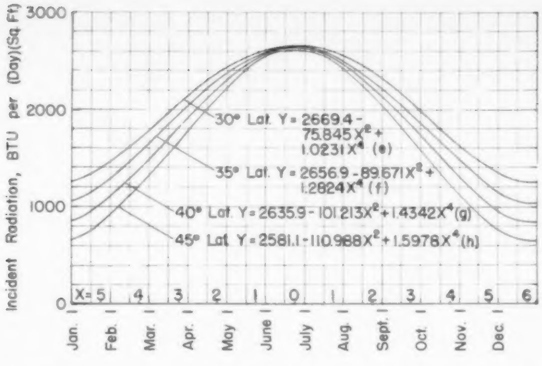


FIG. 1—Daily total direct and sky radiation incident upon a horizontal surface at various north latitudes during cloudless days.

from the *Heating, Ventilating, and Air Conditioning Guide*[1] for the remainder of the months.

(4) The hourly rates of direct radiation incident upon a horizontal surface, south-facing vertical surface, and upon south-facing surfaces tilted 30° and 60° from vertical, were calculated by multiplying the direct solar radiation at normal incidence by the cosine of the angle of incidence determined from formulas (b), (c), and (a), respectively.

(5) Hourly rates of sky radiation were secured from Parmelee's data mentioned earlier. Since there is no information on sky radiation incident upon a tilted surface, this value was estimated by linear interpolation between the value secured for a horizontal and vertical surface.

(6) The total hourly rate of solar radiation was determined by adding the direct and the sky components.

Daily Total Solar Radiation

The daily total radiation incident on the various surfaces was determined by integrating the hourly values over the hours of the day. Figs. 1 through 4 show the daily total solar radiation incident on the various surfaces at 30°, 35°, 40°, and 45° north latitude during cloudless days.

A comparison of the curves in Fig. 1 shows that the horizontal surface intercepts a maximum of radiation in summer, with the amount nearly equal for all four latitudes in late June and early July at about 2650 Btu per day per sq ft. This near equality is explained by the fact that the effect of greater solar altitude near the middle of the day for the southern latitudes is counterbalanced by more daylight hours and by greater solar altitude for the northern latitudes during morning and afternoon hours. The more pronounced change for northern latitude in the number of daylight hours from summer to winter explains the larger decrease in incident radiation from summer to winter for 45° latitude as compared with 30° north latitude. The method of least squares was used to determine the fourth degree polynomials (e), (f), (g), and (h) (see Fig. 1) to fit the curves for 30°, 35°, 40°, and 45° north latitude, respectively. X is the number of months, or fractions thereof, from June 21. The over-all average deviation between the values determined from the polynomials and the corresponding calculated value for the 21st of each month is 15 Btu per sq ft per day.

The curves of Fig. 2 show that the solar radiation incident upon a south-facing vertical surface is at a maximum during winter. It is a maximum then because the lower solar altitudes have a more favorable angle of incidence on a vertical surface as shown by equation (c). The normally higher values for northern latitudes are also explained by consistently lower solar altitudes than for southern latitudes. The dip in the curve for the more northern latitudes in December, which occurs even though the angles of incidence are more favorable then, is due to the increased depletion by the atmosphere and fewer daylight hours. It is noted that the curves for the four latitudes peak at between 1800 and 1900 Btu per day per sq ft. The peaks are very nearly equal because the more favorable angle of incidence for the northern latitudes is offset by more daylight hours and by less depletion by the atmosphere for the southern latitudes.

The curves of Fig. 3 and 4 reveal the importance of proper orientation of solar collector surfaces for the most efficient collection of solar energy. It is noted, for example, that for a surface tilted 30° from the vertical, as compared with a vertical surface, the tilted surface shows a slight increase of incident cloudless day energy during mid-winter, and a substantial increase to a maximum of slightly more than 2200 Btu per day per sq ft during the spring and

FIG. 2—Daily total direct and sky radiation incident upon a vertical south-facing surface at various north latitudes during cloudless days.

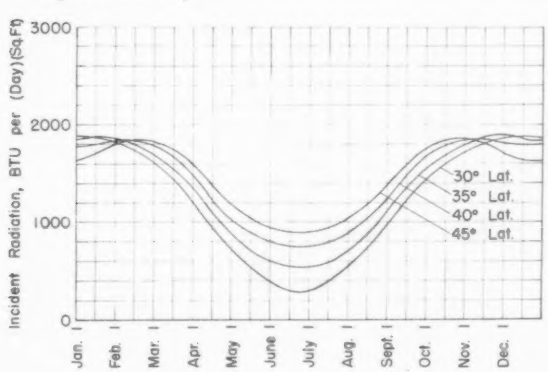
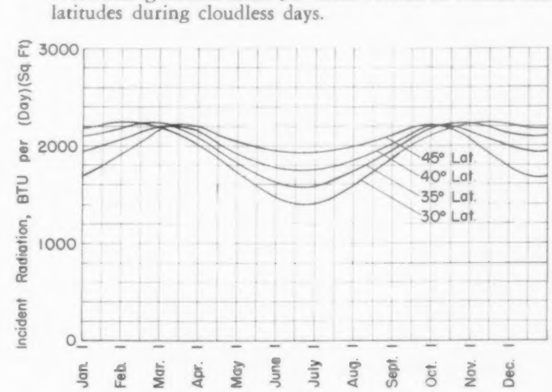


FIG. 3—Daily total direct and sky radiation incident upon a south-facing surface tilted 30° from vertical at various north latitudes during cloudless days.



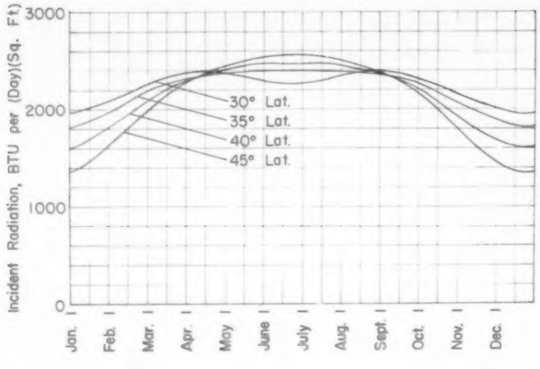


FIG. 4—Daily total direct and sky radiation incident upon a south-facing surface tilted 60° from vertical at various north latitudes during cloudless days.

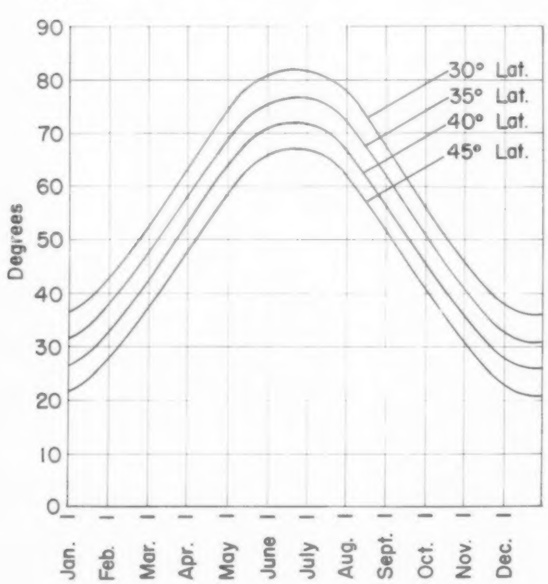
fall months for north latitudes of 30°, 35°, and 40°. For 45° latitude, the tilted surface shows increased incident energy during spring, summer, and fall, and a slight decrease during mid-winter.

Optimum Tilt Angles for Solar Collectors

It is apparent that the optimum tilt angle for a collector of solar radiation will depend on the latitude and on seasonal demand based on the uses to which the collected energy is to be put.

The daily total radiation incident upon a surface, for all practical purposes, will be a maximum if a south-facing surface is tilted so that the sun's rays are perpendicular to it at solar noon. Fig. 5 shows curves which give the number of degrees to tilt a south-facing surface from vertical to make it perpendicular to the sun's rays at solar noon and thus, the optimum tilt angle from vertical for maximum incident solar radiation for various times of the year. However, it is to be noted that calculations using

FIG. 5—Number of degrees to tilt a south-facing surface from vertical to make it perpendicular to the sun's rays at solar noon.



formulas (a) and (d) for June 21st showed a slight increase in daily total incident energy with small increases in the tilt angle from the apparent optimum angle. The small increase occurs because the increase in incident energy during early morning and late afternoon hours due to additional tilting of the surface more than counterbalances the decrease during mid-day. The above situation is true only during mid-summer, when the solar azimuth angles are relatively small during the early morning and late afternoon hours. It should be noted that the above situation would be even more prononunced at more northerly latitudes.

Ratio of Tilted to Horizontal Surface-Incident Radiation

Fig. 6 and 7 show the ratio of tilted to horizontal surface-incident radiation. A polynomial, of the form shown in equation (i) below, was fitted by the method of least squares to each of the curves.

$$Y = a + bX + cX^2 \qquad [i]$$

where X is the slope of the south-facing tilted surface in degrees from vertical; Y is the ratio of tilted to horizontal surface incident radiation.

Table I shows a tabulation of the coefficients of equation (i) for various latitudes and seasons. Equation (i)

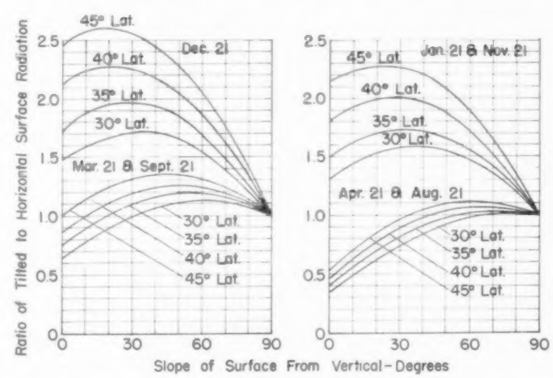
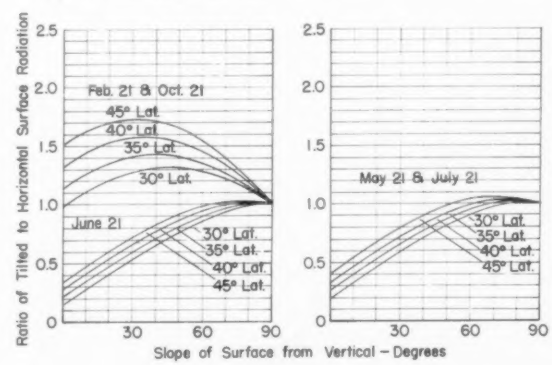


FIG. 6—Ratio of direct and sky radiation incident upon south-facing surfaces with various tilt angles to radiation incident upon a horizontal surface.

FIG. 7—Ratio of direct and sky radiation incident upon south-facing surfaces with various tilt angles to radiation incident upon a horizontal surface.



can be used to secure factors that can be multiplied by the values of Fig. 1, or by the interpolated values of equations (e), (f), (g), and (h) to secure the daily total cloudless-day solar radiation incident upon a south-facing surface at any tilt angle between horizontal and vertical. Ratios for any day of the year can be secured by interpolation between the values secured for the 21st of the months between which the desired day comes.

Variation in Solar-Radiation Intensity with Altitude

The earliest known information on the variation in solar-radiation intensity with altitude was published in 1919 by Kimball.[10] Prior to that time, in cooperation with the Weather Bureau and the Smithsonian Institution, he made studies on the increase in solar-radiation intensity with altitude westward from the Atlantic Coast of the United States. This work was continued and in 1948, Klein[11] summarized work which by that time had included results from 56 plateau and mountain stations, supplemented by information from balloon ascents. He noted that the variation of transmission of solar radiation with altitude depended on the season of the year and the length of the path of the sun's rays (air mass).

Both Klein's and Kimball's data show the increase in atmospheric transmission of solar radiation with altitude as compared to 3/10 of a kilometer (984.2 ft) elevation, because at lower elevations no definite relationship between transmission and elevation could be established, and differences appeared to be more a function of local conditions.

TABLE I

COEFFICIENTS OF THE POLYNOMIAL, $Y = a + bX + cX^2$, (i), FOR THE VARIOUS CURVES OF FIGURES 6 AND 7

Date	Latitude	Coefficient *a*	Coefficient *b*	Coefficient *c*
Dec. 21	30°	1.496	0.012657	−0.0002025
	35°	1.734	.014313	.0002502
	40°	2.132	.012366	.0002774
	45°	2.499	.010621	.0003033
Jan. 21 and Nov. 21	30°	1.322	0.014395	−0.0001999
	35°	1.510	.013339	.0002112
	40°	1.827	.013236	.0002500
	45°	2.154	.012117	.0002776
Feb. 21 and Oct. 21	30°	0.997	0.014531	−0.0001613
	35°	1.141	.015173	.0001860
	40°	1.312	.014250	.0001972
	45°	1.500	.013619	.0002139
Mar. 21 and Sept. 21	30°	0.638	0.016279	−0.0001361
	35°	.768	.015605	.0001445
	40°	.872	.015237	.0001532
	45°	1.011	.015365	.0001722
Apr. 21 and Aug. 21	30°	0.314	0.017447	−0.0001083
	35°	.400	.017659	.0001221
	40°	.492	.016878	.0001249
	45°	.571	.018014	.0001472
May 21 and July 21	30°	0.186	0.016350	−0.0000806
	35°	.244	.016964	.0000944
	40°	.345	.015827	.0000944
	45°	.399	.016884	.0001132
June 21	30°	0.105	0.016696	−0.0000744
	35°	.205	.016145	.0000805
	40°	.277	.016064	.0000889
	45°	.326	.017028	.0001055

Procedure for Calculating Corrections Due to Altitude

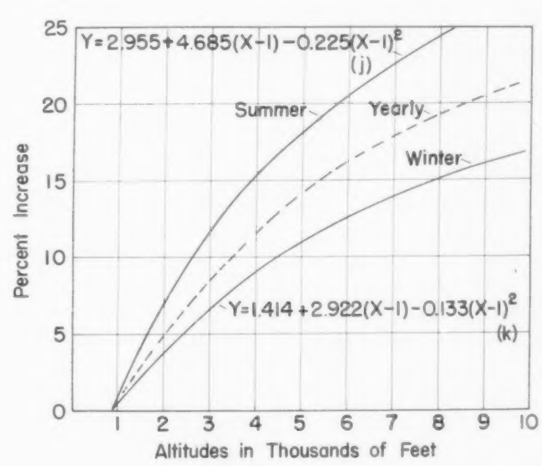
Solar altitudes for June 21 at 40° north latitude for the various daylight hours were integrated by using Simpson's Rule; this integration resulted in an integrated mean solar altitude of 47.7°. A mean solar altitude of 47.7° corresponds to an integrated mean air mass of 1.35 as the secant of the zenith angle of the sun is a good approximation of the air mass. Interpolation of Klein's data for air masses of 1 and 2 was made to get a corresponding value for an air mass of 1.35.

Using the same method used for June 21, the integrated mass for December 21 turned out to be about three; but since data were not available for air masses greater than 2, the data for a winter mass of 2 were used to determine approximate corrections for altitude in winter.

The percentage increase of solar-radiation intensity with altitude was determined for winter and summer conditions according to the increase in the atmospheric transmission coefficients for winter air mass of 2 and summer air mass of 1.35. Fig. 8 shows the percentage increase in solar radiation intensity with altitude for winter and summer conditions. It is of interest to note how closely the curve for yearly mean increase from Kimball's data approximates being an average between the summer and winter increases. The curves were drawn to show no increase with altitude up to 1000 ft above sea level because Klein and Kimball found no definite relationship between atmospheric transmission of radiation and elevations to 1000 ft and also due to good correlation between calculation and recorded values of Blue Hill, Mass., Lincoln, Nebr., and Madison, Wis., which have altitudes above sea level of 672, 1184, and 938 ft, respectively.

The method of least squares was used to determine equations (j) and (k) of Fig. 8 for the summer and winter curves, respectively. These equations can be used between altitudes of 2000 and 10,000 ft above sea level for December 21 and June 21. Percentage increases for any other times of the year can be approximated by interpolation between values given by the two equations.

FIG. 8—Percentage increase of solar radiation intensity with altitude.



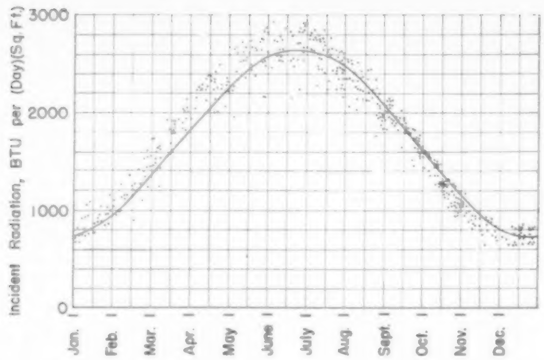


FIG. 9—Comparison between recorded and calculated direct and sky radiation incident upon a horizontal surface at Madison, Wis., during days with 0 to 3/10 cloud cover, 1950 through 1954.

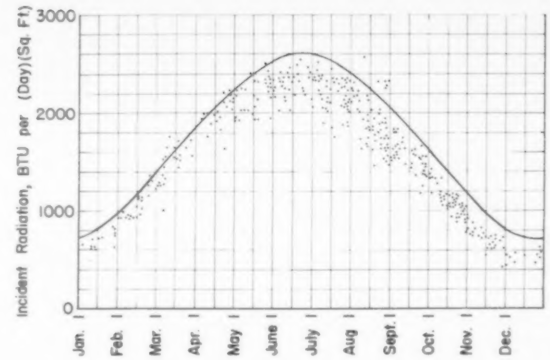


FIG. 12—Comparison between recorded and calculated direct and sky radiation incident upon a horizontal surface at East Lansing, Mich., during days with 0 to 3/10 cloud cover, 1950 through 1954.

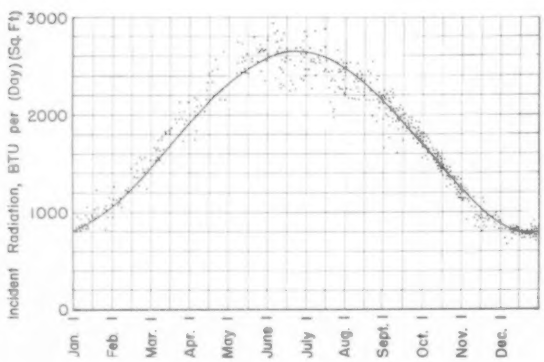


FIG. 10—Comparison between recorded and calculated direct and sky radiation incident upon a horizontal surface at Lincoln, Nebr., during days with 0 to 3/10 cloud cover, 1950 through 1954.

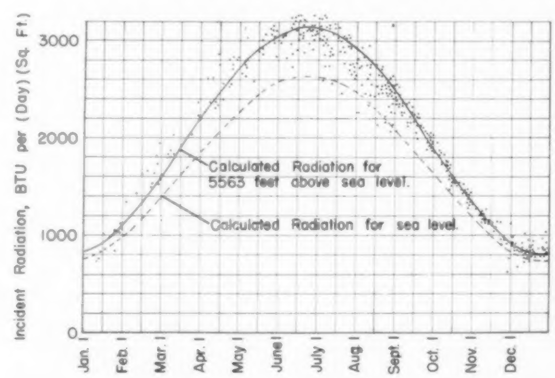


FIG. 13—Comparison between recorded and calculated direct and sky radiation incident upon a horizontal surface at Lander, Wyo., during days with 0 to 3/10 cloud cover, 1950 through 1954.

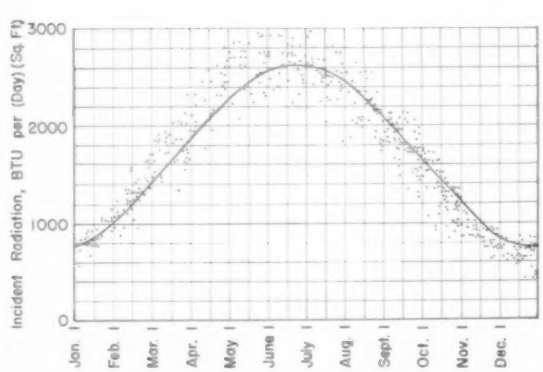


FIG. 11—Comparison between recorded and calculated direct and sky radiation incident upon a horizontal surface at Blue Hill, Mass., during days with 0 to 3/10 cloud cover, 1950 through 1954.

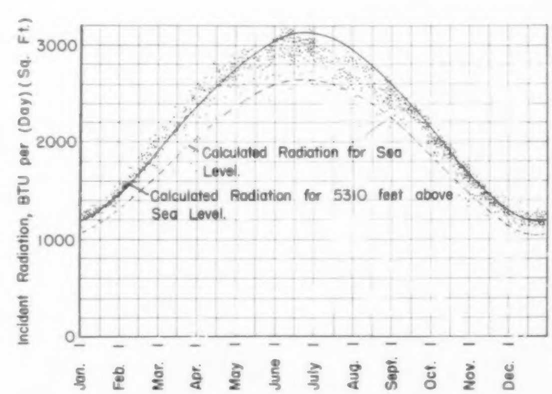


FIG. 14—Comparison between recorded and calculated direct and sky radiation incident upon a horizontal surface at Albuquerque, N.M., during days with 0 to 3/10 cloud cover, 1950 through 1954.

COMPARISON BETWEEN CALCULATED CLOUDLESS DAY AND RECORDED CLEAR DAY RADIATION

There is a network of Weather Bureau Stations in the United States which measure and record solar radiation incident upon a horizontal surface. The first solar station in the United States was started in 1911 at Madison, Wis. The number of stations has increased from 10 in 1940 to 25 in 1949, and to 75 today. Daily total values of solar radiation incident upon horizontal surfaces are published by the Weather Bureau in *Climatological Data, National Summary.*[19] In addition to the data for radiation on horizontal surfaces, a station at Blue Hill, Mass., measures and publishes data for radiation incident upon vertical surfaces facing north, south, east, and west.

Procedure for Comparison between Calculated Cloudless-Day and Recorded Clear-Day Radiation

Supplements of *Local Climatological Data*[20] were secured from the United States for Lincoln, Nebr., Madison, Wis., Boston, Mass., Lander, Wyo., Albuquerque, N.M., and Lansing, Mich., for the five-year period 1950 through 1954. Dates when the average sky cover from sunrise to sunset was 3/10 or less were recorded. Daily total incident radiation was then secured for the recorded clear days for a horizontal surface at each of the stations and for a south-facing vertical surface at Blue Hill, Mass.

Calculated solar radiation during cloudless days incident upon a horizontal surface for the 21st of each month was determined for each of the stations by interpolating between values secured from the equations in Fig. 1 for the latitude of each station. Equations (j) and (k) of Fig. 8 were used to correct the calculated values of Lander and Albuquerque for altitudes of 5563 ft and 5310 ft above sea level, respectively.

Curves showing the calculated incident cloudless-day radiation were constructed for each of the stations. Plots of points representing the recorded clear-day radiation during clear days were made. Figs. 9 to 14 show the comparison between calculated and recorded clear-day solar radiation incident upon horizontal surfaces for the stations mentioned, and Fig. 15 shows the comparison for a south-facing vertical surface at Blue Hill, Mass. It is evident that the calculated curves, based on assumed standard atmospheric conditions, have reasonably good correlation with observed radiation except at East Lansing, where the computed values are consistently too high, varying from about 25 per cent to 10 per cent too high for winter and summer, respectively. A possible explanation for the consistently low recorded values at East Lansing may be due to the fact that Michigan is surrounded, to a great extent, by large bodies of water over which the masses of air must move in their predominant easterly movement. The bodies of water and the large industrial activity in the whole area undoubtedly tend to increase the haziness and smoke content of the atmosphere to above the assumed amount for a normal atmosphere.

It is noted, in each case, that the calculated values are low during the spring and early summer period and high during the last part of October and first part of November. This difference is possibly due to higher atmospheric moisture content than assumed during the October-November period and to a lower moisture content than assumed during the spring months as indicated by data in a Weather Bureau publication[21] summarizing monthly mean precipitable water for all days in the United States.

The variation noted for all stations can be attributed, in part, to varying cloud amounts because the recorded values used were for days with average cloud cover betweeen 0 and 3/10. Additional variation may be caused by occasional presence of dust or moisture on the glass cover of, or by improper leveling of, the measuring pyrheliometer.

In addition to the explanation given for the variation of solar radiation on a horizontal surface, the vertical surface will be subjected to varying amounts of reflected radiation from the ground. The high recorded values in Fig. 15 can reasonably be attributed to increased ground reflection when the ground is covered with snow.

FIG. 15—Comparison between recorded and calculated direct and sky radiation incident upon a vertical surface at Blue Hill, Mass., during days with 0 to 3/10 cloud cover, 1950 through 1954.

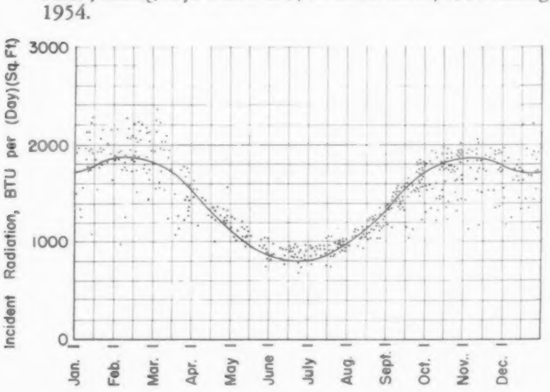
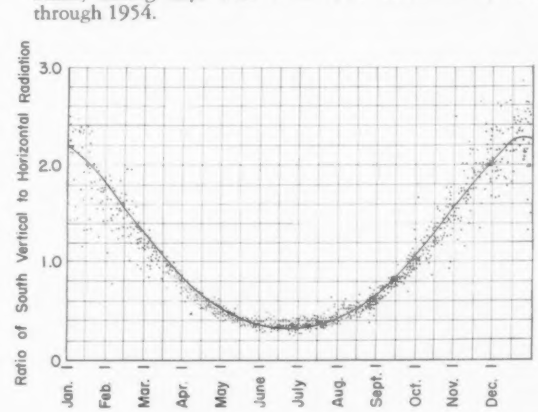


FIG. 16—Comparison between actual and calculated ratio of total radiation incident upon a south-facing vertical surface to that incident upon a horizontal surface at Blue Hill, Mass., during days with 0 to 7/10 cloud cover, 1950 through 1954.



COMPARISON BETWEEN CALCULATED AND OBSERVED RATIO OF VERTICAL TO HORIZONTAL SURFACE INCIDENT RADIATION

The only possible check of the calculated ratios of solar energy incident upon south-facing surfaces to that incident upon a horizontal surface as presented in Fig. 6 and 7, is to check the ratio of south-facing vertical to horizontal surface incident radiation for Blue Hill, Mass. This was done as shown in Fig. 16 for days during 1950 through 1954, when the average sky cover from sunrise to sunset was classified as clear or partly cloudy (0 to 7/10 cloud cover, inclusively). Only clear and partly cloudy days were used for this comparison because only a very small portion of the total radiation is available during cloudy days.

It is noted that Fig. 16 shows considerably more scatter of points during winter months than during summer months. The very high ratios during the winter can be attributed to the increased radiation incident upon the south-facing vertical surface owing to increased reflection from the ground caused by snow cover, which would affect the vertical surface more than the horizontal surface. The observed ratios which fall considerably below the calculated ratios occurred on the relatively cloudy days because with increased cloudiness, the radiation tends to become equal in all directions, or the the ratio tends toward unity.

EFFECT OF CLOUDS ON SOLAR RADIATION INTENSITY

So far the discussion presented for calculated solar radiation intensity has been for cloudless skies, and the observed values referred to have been for clear days. Because of the great effect clouds have on solar radiation, it is one of the most important considerations in determining the availability of solar energy.

Fritz[4] states that if we look at the earth as a whole, the planet reflects about 35 per cent of the solar radiation incident upon it back to space and that clouds are the major cause for this reflection. The transmission of solar radiation through clouds depends on the cloud type, the mean free path of the sun's rays through the cloud, drop size and distribution, and liquid-water content of the clouds. Because of the difficulty involved in approximating the parameters mentioned, and owing to the non-homogeneous nature of clouds, Fritz,[9] Kimball,[10] and others suggest correlating the measurements of solar radiation at a few stations with some other parameter, such as percentage of possible sunshine, which is observed at many places.

Procedure and Results for Determining the Effect of Clouds

The mean daily recorded solar radiation on a horizontal surface and the mean percentage of possible sunshine were secured from *Climatological Data, National Summary*[19] for Albuquerque, Blue Hill, Madison, Lincoln, and Lander for each month during the period 1950 through 1954. Calculated total radiation incident upon a horizontal surface for cloudless days was calculated for each station for the 15th of each month using the equations in Fig. 1 and interpolating for the latitude of the respective stations. The values secured from the computation for Lander and Albuquerque were corrected for the altitude of the respective stations. Fig. 17 shows the correlation between the ratio of mean daily recorded radiation to calculated cloudless day radiation and percentage of possible sunshine. The method of least squares was used to determine the linear equation (1). The coefficient of correlation between the ratio and percentage of possible sunshine is 0.82 and the standard error of estimate is 6.4 per cent.

CONCLUSIONS

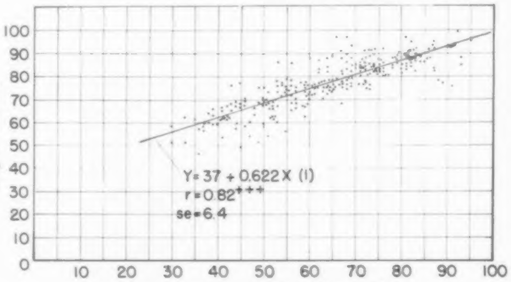
The amount of solar radiation available is very large but has the disadvantage of being intermittent and relatively low in intensity.

The cloudless-day solar radiation intercepted by a horizontal surface is at a maximum and has little latitudinal variation during mid-summer in the United States. The amount of radiation incident upon a horizontal surface during mid-winter decreases to about 50 per cent and 25 per cent of the summer value at 30° and 45° north latitude, respectively.

The increase in solar-radiation intensity with altitude above sea level as we progress from east to west in the United States is significant, the increase being greater in summer than in winter.

The amount of solar radiation incident on a surface is affected to a very great extent by the orientation of the surface. The proper tilt angle of a south-facing surface is a function of the latitude and season of the year. Little increase in incident solar radiation is noted for an orientation other than horizontal during mid-summer, while during mid-winter the distinct advantage of a surface which is nearly vertical is evident. A south-facing surface with optimum tilt angle will have approximately 5 per cent and 15 per cent more incident cloudless-day radiation than a vertical surface on December 21 at 45° and 30° north latitude, respectively. The optimum tilt angle from vertical increases from December to June when the optimum surface would be very nearly horizontal.

FIG. 17—**Relationship between ratio of actual to calculated cloudless day radiation, I/I_o, and percentage of possible sunshine.**



The curves and polynomials developed for estimating (1) the amount of solar radiation available on horizontal surfaces during cloudless days; (2) the ratio of radiation incident upon a south-facing tilted surface to that incident on a horizontal surface; and (3) the increase in radiation with altitude, show reasonably good correlation with actual recorded data except for the Great Lakes Region, where the calculated values are 10 per cent to 25 per cent high, depending on the season.

The regression equation relating the ratio of actual to calculated cloudless-day radiation and percentage of possible sunshine, provide a method for estimating the average solar radiation for any season at a great many places. The estimates apply only to average values and are subject to large deviations in individual cases due to local variations in conditions such as atmospheric pollution, ground reflection, and snow cover.

There is need for verification of the ratio of solar radiation incident upon tilted surfaces to that incident on horizontal surfaces further than that presented in this paper, as the only verification used was the ratio of vertical to horizontal incident radiation at one station. It is also possible that these ratios could be refined further by determining the effect of cloudiness upon them as it would be expected that the ratios would tend toward unity with increased cloudiness.

There is also a need for an intensive study of atmospheric moisture conditions and an extension of the data for direct solar radiation at direct incidence as presented in the *Heating and Ventilating Guide* and by Hutchinson and Chapman to include a wider range of atmospheric moisture conditions.

Methods of describing the variability of solar radiation availability in terms of average distribution of, and probabilities of, numbers and sequences of days with various categories of incident radiation are needed. The latter can be accomplished when more and longer records of recorded incident radiation are available.

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NOTES ON PERFORMANCE DESIGN OF PARABOLIC SOLAR FURNACES

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The characteristics of the solar image formed by an ideal, perfectly reflective paraboloid are presented. The solar furnace heat losses occurring with the use of an actual, necessarily imperfect paraboloid are enumerated and roughly evaluated. No single loss is found to be large, but all of them combine to significantly reduce solar furnace performance as compared with that theoretically obtainable with a perfect paraboloid. The maximum temperatures which appear practicably attainable by solar furnaces are calculated These maximum practicable temperatures are found to be noticeably higher than those presently attained. It is concluded that such higher temperatures, if desired, can actually be attained with a solar furnace provided that very careful attention is given to all furnace design details.

INTRODUCTORY

Most persons contemplating footing the bill for the construction of a parabolic solar furnace would like to know in advance how the completed apparatus will perform. Specifically, the prospective purchaser would like to know the diameter of the concentrated image, or "hot spot", which the furnace can produce; the solar radiation intensity to be expected upon the face of this hot spot; and the approximate maximum temperature which will be attained at this spot. With a little study all of these questions could have been answered to good accuracy at any time within the last fifty years. Until recently no one appears to have applied himself to the matter, presumably because of a certain lack of any interested solar furnace purchasers. But prospective purchasers are now appearing, and over the past two or three years increasing technical attention has been given to the performance possibilities of these solar furnaces.[1 2 3 4]

In two important respects a well-designed solar furnace appears uniquely superior to all other types of conventional high-temperature research furnaces:

(1) A solar furnace can provide an exceptionally "clean" working atmosphere, uncontaminated by extraneous chemical impurities or electrical effects.

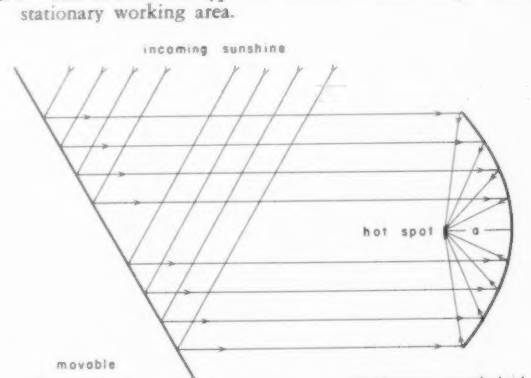
(2) The radiation intensity upon test samples in a solar furnace can be rapidly and accurately controlled or varied.

A highly uncontaminated and highly controllable high temperature heat source is of great interest in the development and improvement of the high-temperature-resistant alloys, ceramics, and cermets which are finding ever wider need in both military and industrial applications. Hence solar furnaces are objects of increasing commercial attention. For many types of high temperature research work the inherent special advantages of solar furnaces appear to outweigh their inherent limitations. These last are: (1) solar furnaces must be located in a relatively cloudless area; (2) only intermittent test runs (at most about 8 hours) can be made; (3) only small samples can be treated at one time, ranging (very roughly) from a few ounces for small furnaces up to about 10 lb batches for a quite large furnace; (4) solar furnace costs are moderately high for a moderate-sized high-temperature furnace (spot diameter 1 or 2 in.), and increase rapidly to become extremely high for large high-temperature furnaces with spot diameters in excess of 4 inches.

The maximum temperatures presently attained by solar furnaces are on the order of 3000 to 3500 C, which is about the same as that attained by conventional ultra-high temperature research furnaces. It appears that, by very careful design, solar furnaces can be built for research up to 4000 C, perhaps even somewhat higher. A large solar furnace can produce a larger but no "hotter" spot than a smaller furnace of the same relative dimensions. Hence the advantage of a large furnace is solely in the larger size of the high temperature working area, and not in any increase in temperature. If a high-intensity furnace with a hot spot more than an inch or two in diameter is required, the furnace must be a very large structure. For example, to produce a high-intensity hot spot 5 in. in diameter would require a paraboloidal reflector with a diameter about equal to the height of a ten story building.

Parabolic solar furnaces are so arranged that the sun's rays are directed at a parabolic reflector and thereby concentrated at the focal plane of the paraboloid. The desired

FIG. 1—The two mirror type of furnace is used to provide a stationary working area.



high temperature research work is conducted either at this concentrated image in the focal plane or within a black-body cavity whose opening is at the concentrated image. The paraboloid may be aimed directly and continuously at the sun if desired, but this makes for very awkward working conditions at the moving focal plane. A fixed focal plane can be achieved by using a "two-mirror" type of furnace, in which the paraboloid is held stationary and the sun aimed directly at it by means of a suitably placed and moving auxiliary plane mirror called the "heliostat". A schematic view of the two-mirror arrangement is shown in Fig. 1. The well-known large furnace built by Trombe[3] at Montlouis, France, is an example of such a furnace.

This article presents the basic equations applicable to the performance design of a parabolic solar furnace. This type of solar heat collector is inherently simpler in operating principles than a flat-plate collector. But any appearance of utter simplicity is completely deceptive. Just as with any other type of solar heat collector, if a parabolic solar furnace is to perform in accordance with design expectations, its basic operating principles must be thoroughly understood, and painstaking attention must be given to design details.

TABLE I

PRINCIPAL SYMBOLS USED

a	Paraboloid focal length, ft.
C	Concentration ratio of a perfect paraboloid, dimensionless.
C_a	Concentration ratio of a solar furnace, dimensionless.
d	Hot spot diameter, ft.
F	Furnace factor, dimensionless.
q_f	Solar radiation intensity upon hot spot, Btu/sq ft-hr.
q_i	Direct sunshine intensity at furnace site, Btu/sq ft-hr.
q_s	Radiation intensity at surface of sun, Btu/sq ft-hr.
T	Temperature, °F absolute.
α	Angular diameter of sun's disc, radians.
α_r	Solar absorptivity of test sample, dimensionless.
ϵ	Emissivity of test sample, dimensionless.
η	Furnace "transmissivity factors", dimensionless.
θ	Angle between paraboloid principal axis and paraboloid radius from focal point, degrees.
θ_1	Rim angle of paraboloid, degrees.
ρ	Paraboloid radius from focal point, ft.
σ	Stefan-Boltzman constant, Btu/sq ft-hr (°F abs).[4]

SOLAR IMAGE FORMED BY A PERFECT PARABOLOID

A perfect paraboloid we define as one whose surface is a geometrically true paraboloid and is perfectly reflective. If such a paraboloid is aimed directly at the center of the sun's disc, a circular composite image is formed at the focal plane by reflections from all parts of the paraboloid. This composite image consists of a circular center portion of maximum and uniform intensity — the "hot spot" — which is surrounded by a fringe of radially decreasing intensity. (See Figs. 2 and 3.)

The diameter of the hot spot is given by:

$$d = \mathrm{a}\,\alpha \qquad [1]$$

The meaning and dimensions of all principal symbols used in this article are summarized in Table I.

The diameter of the sun's disc has an average value of 0.00931 radian. It varies from 0.00948 radian in January,

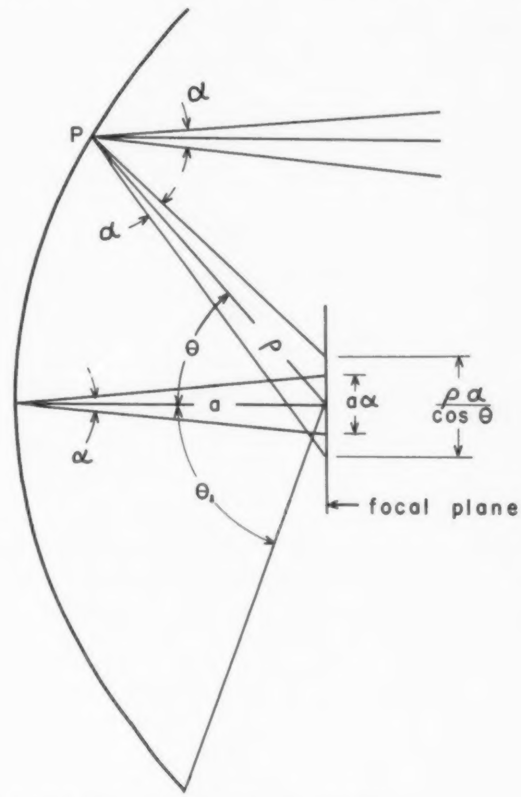
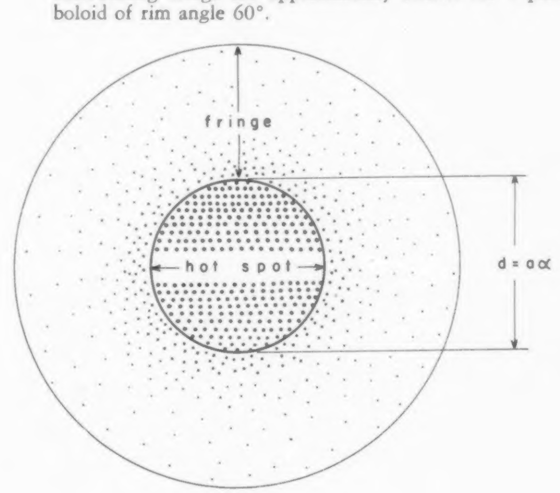


FIG. 2—Solar image formation by a paraboloid.

FIG. 3—Composite solar image formed at the focal plane by a paraboloid. The relative diameters of the hot spot and the surrounding fringe are approximately correct for a paraboloid of rim angle 60°.



when the earth is closest to the sun, to 0.00917 radian in July, when the earth is farthest from the sun. Hence the hot spot diameter will be very slightly larger in January than in July.

The concentration ratio C produced at the hot spot is defined as the ratio between the theoretical solar radiation intensity upon the hot spot and the unconcentrated direct sunshine intensity at the furnace site:

$$C \equiv \frac{q_t}{q_1} \quad [2]$$

This ratio is calculated in Appendix I and, to a close approximation, is found to be a simple function of the paraboloid rim angle and the sun's angular diameter:

$$C = \frac{4}{a^2} \sin^2 \theta_1 \quad [3]$$

Hence, for a perfect paraboloid:

$$q_t = q_1 \frac{4}{a^2} \sin^2 \theta_1 \quad [4]$$

The factor $4/a^2$ appearing in the above equation has an average value of 46,200, ranging from a minimum of about 44,500 in January to a maximum of about 47,500 in July. This variation should be taken into account in connection with accurate calorimetric determinations of solar furnace concentration ratios.

If the sun is assumed to be a uniform sphere whose surface radiation is q_s, and if the fractional reduction of direct sunshine in passing through the atmosphere is T, it can be readily shown that:

$$q_1 = \mathrm{T} \frac{a^2}{4} q_s \quad [5]$$

Hence we may express Equation [4] as:

$$q_t = \mathrm{T}\ q_s \sin^2 \theta_1 \quad [6]$$

It will be noted from the above equation that, in the absence of atmospheric transmissivity losses, a perfect paraboloid of rim angle 90° would produce a radiation intensity upon the hot spot equal to the radiation intensity of the sun's surface. Also it will be noted that a given paraboloid within the earth's atmosphere will produce a radiation intensity upon the hot spot which is directly proportional to the atmospheric transmissivity factor T, and independent of the sun's distance. In many cases the factor T can be expected to be slightly higher in summer than in winter, because of the shorter path length of sunshine through the atmosphere at higher angular solar altitudes. This situation, together with the longer hours of sunshine available in the summer, probably favors Mediterranean-type ("summer dry") climates as preferred locations for solar furnaces which are to be used continuously.

ALLOWANCE FOR FURNACE TRANSMISSION LOSSES

An actual paraboloidal solar furnace will have a hot spot of the same diameter as that of a perfect paraboloid, but the concentration ratio C_a of the actual furnace will be less than that of the perfect paraboloid by a suitable reduction factor F, which we call the "furnace factor":

$$C_a = FC \quad [7]$$

Hence the radiation intensity incident upon the hot spot of an actual solar furnace will be:

$$q_t = q_1 F \frac{4}{a^2} \sin^2 \theta_1 \quad [8]$$

This furnace factor F is the catchall product of a series of transmissivity factors allowing for all solar energy losses in transit through the apparatus. The furnace factor may be expressed:

$$F = (\eta_1\ \eta_2\ \eta_3\ \ldots\ \eta_n) \quad [9]$$

As an illustrative example of the meaning and approximate magnitudes of the various transmissivity factors, we may consider the case of a two-mirror parabolic furnace. We assume that both the heliostat and the paraboloid mirrors of the furnace are built up of many individual segments of back-silvered glass. We further assume that the hearth at the hot spot is supported by some sort of tower, and that the furnace has some type of flux-control diaphragm which produces some shading even when "wide open". The resulting losses are briefly discussed and roughly evaluated in the paragraphs that follow.

Some solar energy will be lost by glass absorption. The sunshine must make four trips through the glass: in and out of the heliostat mirror and in and out of the paraboloid mirror. For clear glasses ranging from ⅛ to ¼ in. in thickness, of types which would be used in solar furnace design, values of the glass transmissivity factor η_t can be expected to range from about 0.94 to 0.98 per pass.[6 7] The exact value, of course, depends upon the particular glass chosen. Glass transmissivities will decrease slightly with increasing incident angle of sunshine upon the mirror, a factor which must be allowed for in exact calculations.

We can allow for the reflectivity of each silvered surface with a transmissivity factor η_r. This factor will vary with the quality of the silvering, the wavelength distribution of the incident sunshine, and with incident angle of sunshine upon the surface. Reflectivity increases slightly with increasing incident angle. A reasonable assumption is that the surface reflectivity transmissivity factor will lie in the range of 0.91 - 0.95 for each silvered surface.[8]

We then include a transmissivity factor η_g for each mirror to allow for the effect of geometrical imperfections of the mirror surfaces. The two heliostat mirror surfaces will not be truly plane and parallel, and likewise the two paraboloidal mirror surfaces will not be exactly true. We presently judge that, if the mirrors are formed by a grinding or slumping process whose cost will be somewhere within reason for a solar furnace, the appropriate geometrical perfection transmissivity factor will probably lie in the range of 0.90 - 0.96 per mirror. This factor might be considerably lower in the case of paraboloid mirrors formed by very inexpensive methods, such as clamping flat mirrors to an approximation of the desired curvature.

The next transmissivity factor we consider is the mirror frame shading transmissivity factor η_f for each mirror. Since in our assumed furnace both the paraboloid and the

heliostat mirrors are built up of individual segments, there must be a non-reflecting space or frame around each mirror segment. If the segments are, say, square, 1 ft on a side, and separated by a ¼ in. crack, then the non-reflecting crack area is about 4 per cent. We must take this into account for both the heliostat and the paraboloid. We judge that reasonable values of the mirror frame shading transmissivity factor should range between 0.94 and 0.98 per mirror, depending upon the care and expense taken in construction details.

The tower and the apparatus at the hearth will contribute a shading loss. A reasonable estimate of the transmissivity factor η_s to allow for this loss should lie in the range of 0.85 to 0.95, depending, of course, on the design of the tower and its size relative to the entire paraboloid. It should be noted that shading produced near the center of the paraboloid will cause a greater percentage of concentration drop than the percentage of shading. This effect can be calculated, and it will be found that for a paraboloid of rim angle 60° (more or less typical of solar furnace construction) center shading of 1 per cent of the projected paraboloid area will produce nearly a 2 per cent drop in concentration. Similarly, a thin rod along a paraboloid radius — to which a tower leg is roughly equivalent — will produce a greater percentage concentration drop than the percentage of shading. In the case of the rod parallel to the radius and extending from center to rim of the paraboloid, it can be shown that, for a paraboloid of rim angle 60°, one per cent of shading by the rod will produce approximately a 1.25 per cent drop in concentration ratio. These effects must be allowed for in calculations. It is evident that a furnace should be designed to reduce all shading, and especially center shading, to an absolute minimum.

It was mentioned that our hypothetical furnace will have shading produced by the flux control diaphragm, even when it is fully open. We assign an appropriate transmissivity coefficient η_c, and guess that its value should lie in the range 0.95 - 0.99. The exact value, of course, will depend upon the design and placing of the flux control diaphragm.

Finally, in what may seem a distressingly long listing of the losses to be expected from our hypothetical furnace, the matter of mirror segment alignment should be considered. Both the heliostat and the paraboloid will be built up of many small segments, perhaps thousands if the furnace is a large one. These segments must be adjusted to proper alignment during construction, and they can be re-aligned only at intervals once the furnace is placed in operation. The question naturally arises: will they stay aligned? Probably, to some degree, they will not. Wind, weather, thermal strains, and other causes can be expected to throw at least some of the mirror segments partially out of alignment. The designer must seek to minimize this factor, also to estimate or measure it, and to allow for it. We assign a transmissivity factor η_a to allow for this effect, and presently guess its value as lying between 0.95 and 0.99 for a well-designed and carefully constructed furnace.

It now appears that we have considered and roughly estimated all the depletion effects which will lower the performance of our hypothetical furnace as compared with a perfect paraboloid. The various transmissivity factors which we have discussed are summarized in Table II. For a two-mirror furnace of the type assumed, the furnace factor will be:

$$F = (\eta_{t1}^2 \ \eta_{r1} \ \eta_{g1} \ \eta_{f1} \ \eta_s \ \eta_c \eta_a \ \eta_{t2}^2 \ \eta_{r2} \ \eta_{g2} \ \eta_{f2}) \quad [10]$$

In the above equation the subscripts 1 and 2 refer to the heliostat and to the paraboloid mirrors respectively. No single loss is exorbitant, but the combination of all of them reduces the furnace performance very significantly below that of a perfect paraboloid. Combining all our low estimates of the various transmissivity factors results in a furnace factor of 0.35; combining all the high estimates results in a furnace factor of 0.69. We judge that a reasonably well-designed two-mirror parabolic furnace should exhibit a furnace factor somewhere within this range, and with very careful design we believe that values near the top of the range can be attained.*

TABLE II

TYPICAL TRANSMISSIVITY FACTORS FOR A TWO-MIRROR PARABOLIC FURNACE

Symbol	Factor	Estimated Value Low	High
η_t	Glass transmissivity, per pass	.94	.98
η_r	Surface reflectivity, per surface	.91	.95
η_g	Geometrical imperfections, per mirror	.90	.96
η_f	Mirror frame shading, per mirror	.94	.98
η_s	Tower shading	.85	.95
η_c	Flux control shading	.95	.99
η_a	Alignment factor	.95	.99
	Overall furnace factor F	.35	.69

Fig. 4 presents the concentration ratios which can be attained with paraboloids of various rim angles and with furnace factors ranging from 0.30 to 0.60.

It is very important in solar furnace design that the furnace factor of the proposed furnace be both as high as practicable, and known as accurately as possible. Slight changes in furnace factor can necessitate large changes in design size in order to produce a desired concentration ratio. We believe that the necessary maximizing and accurate determination of furnace factor is best approached through experimental heat transfer testing of proposed furnace components under sunshine conditions. Individual components of the proposed furnace should be tested for glass transmittance, reflectivity, geometrical

*Subsequent to the preparation of this article it was found that a similar approach to the problem of determining solar furnace efficiency had already been made, in reports prepared for a branch of the U.S. Air Force by Loh, Duwez, Hiester, & Tietz,[11] and by De La Rue, Tietz, & Hiester.[12] In the second of these reports the authors define a furnace efficiency E, which includes atmospheric depletion effects, and is numerically equal to τF in our nomenclature. The same authors also define a geometrical perfection term γ, which in our nomenclature is equal to $\eta_{g1} \ \eta_{g2} \ \eta_a$. They have calculated values of E and γ for several existing solar furnaces.

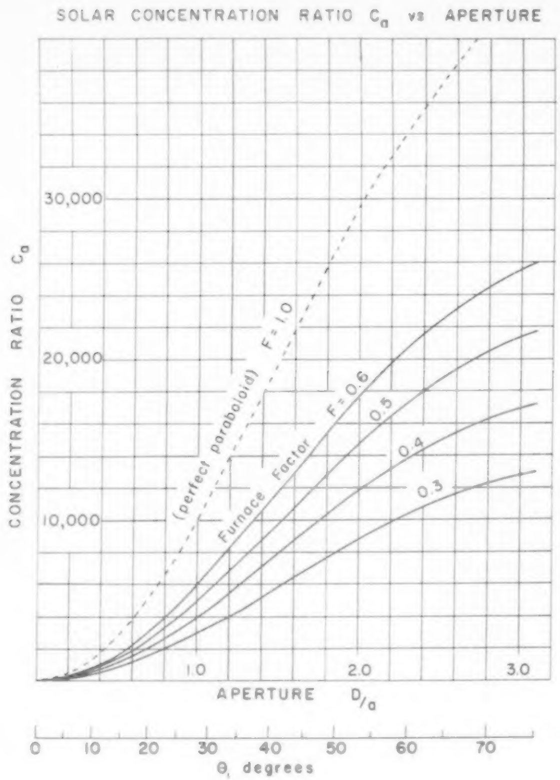


FIG. 4—Concentration ratios attained by furnaces of various aperture ratios and furnace factors.

aberrations, etc., and, finally, small sub-assemblies of the actual proposed furnace should be performance tested in order to build up a picture from which the performance of the completed furnace may be accurately predicted.

MAXIMUM TEMPERATURES ATTAINABLE WITH SOLAR FURNACES

The maximum temperatures which can be attained by a sample whose exposed face lies in the focal plane at the hot spot of a given furnace depends upon the direct sunshine intensity at the site, the concentration ratio of the furnace, and the relation between the solar absorptivity and emissivity of the sample. We first estimate the intensity of direct sunshine which may be expected.

The most logical solar furnace climatic area in the United States is somewhere in the Southwest. Within this area direct sunshine intensity measurements at present are made regularly at three stations: Table Mountain, California (about 60 miles northwest of San Bernardino); Albuquerque, New Mexico; and Tucson, Arizona. The records from the first two of these stations have been regularly published[9] for some time, and serve as a good basis for engineering estimates. Typical values for 1955 are shown in Fig. 5. The Table Mt. station is located at an elevation of 7500 ft in a clear mountainous area. Direct sunshine intensities reported from this station can be taken as typical of those which might be expected at a furnace site chosen predominantly for high sunshine intensities. The Albuquerque pyrheliometric station is located at the city airport. Although the elevation is 5500 ft (which is favorable to obtaining relatively high solar intensities) the location is noticeably dusty and occasionally somewhat smoky. We believe that sunshine intensities at least as high as those found at this station can be expected in most of the valley areas of the Southwest. In the clearer valley areas direct sunshine intensities somewhat higher than those reported from Albuquerque can probably be expected fairly regularly.

Based on Fig. 5 and similar data we consider that the following are reasonable engineering estimates of working values of direct sunshine intensities to be expected in the southwest:

High-elevation mountain-area locations chosen primarily for high solar intensities:
- Occasional peak value........................360 Btu/sq ft-hr.
- Working value which can be regularly expected..........................320 Btu/sq ft-hr.

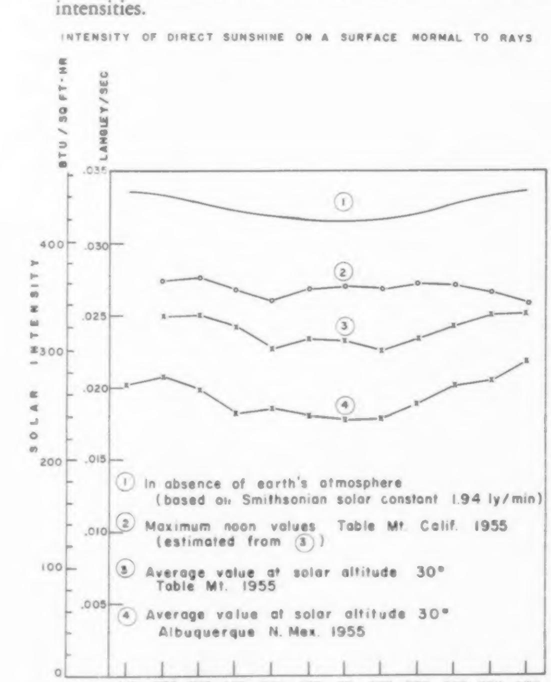
Average southwestern locations:
- Working value which can be regularly expected (and fairly often exceeded)........................260 Btu/sq ft-hr.

The "best" working location for a solar furnace is of course not necessarily simply the one with the highest intensity of direct sunshine. Conditions of cloudiness and convenient accessibility must also be considered.

In addition to estimating direct sunshine intensity at the site, it is necessary in estimating maximum attainable temperatures to consider the concentration ratio of the furnace, and the solar absorptivity and the emissivity of the sample under test.

In many cases it is reasonable to assume that the sample will lie within the hot spot at the focal plane and that by

FIG. 5—Typical measured values of southwestern direct sunshine intensities.



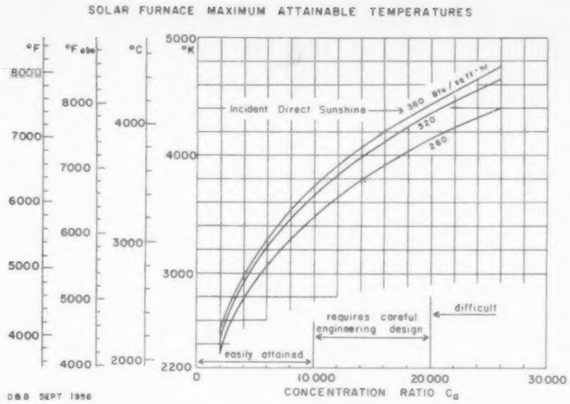


FIG. 6—Approximate maximum temperatures attainable by solar furnaces.

far the largest portion of the sample heat loss will be by radiation from the front (assumed plane) face of the sample. In such a case we may equate incoming sunshine heat gain to outgoing radiation loss:

$$a_r\ C_a\ q_i = \epsilon\ \sigma\ T^4 \qquad [11]$$

or, solving for T:

$$T = \left(\frac{a_r\ C_a\ q_i}{\epsilon\ \sigma}\right)^{1/4} \qquad [12]$$

If the further assumption is made that the sample absorptivity is equal to its emissivity, the equation becomes:

$$T = \left(\frac{C_a\ q_i}{\sigma}\right)^{1/4} \qquad [13]$$

Fig. 6 is a plot of the above equation. It presents, we believe, a good approximation to the *maximum* temperatures attainable by samples at the hot spot in the focal plane of a solar furnace.

The assumption that absorptivity is equal to emissivity is exactly true if the sample temperature is equal to the source temperature. It tends to be approximately true in the case of solar furnace samples operating at a very high temperature, as such samples are approaching (very roughly) the apparent temperature of the sun. Also, in defense of the approximation involved in determining sample temperature through the assumption that absorptivity is equal to emissivity, it is to be noted that the fourth-power relationship in Equation [13] is such that a given percentage error in the ratio a_r/ϵ will produce only about one-fourth as large a percentage error in the value of T. All in all, we presently consider this equation gives a good engineering estimate of the maximum temperatures attainable both by many types of samples placed at the hot spot of a furnace and by blackbody cavities opening to the hot spot.

It will be noted from Fig. 4 that solar furnace concentration ratios of 20,000 or over appear practicably attainable, and from Fig. 6 it appears that such concentration ratios should produce maximum temperatures in excess of 4000 C. Such concentration ratios and temperatures do not seem to have been reliably reported as attained by any present solar furnace. It is our belief that such temperatures, if desired, *can* be attained with a solar furnace, provided that great care is taken in designing the furnace to the necessarily high furnace factor.

SUMMARY AND CONCLUSIONS

A parabolic reflector appears the most logical type of solar heat collector for use in producing very high temperatures. The design principles of this type of collector are relatively simple, but careful attention to all details is necessary to produce the best practicable design. Solar furnace performance falls short of the performance of a perfectly reflecting paraboloid because of a multiplicity of small heat losses, not because of any single large loss. The causes of all of these small heat losses can be identified and evaluated. By taking care to minimize each of them to the highest practicable extent, it would appear that a substantially improved solar furnace could be built. Such improvement might be either in a cost direction, by designing a somewhat smaller but more efficient furnace which would give the same performance as has already been achieved; or the improvement could be in the direction of higher performance, in which a relatively high rim angle furnace, with careful design, could be expected to produce considerably higher concentration ratios and temperatures than have yet been achieved.

APPENDIX I

DERIVATION OF EQUATION OF PERFECT PARABOLOID CONCENTRATION RATIO

The solar image formed at the focal plane by reflection from the vertex of the paraboloid will be a circle — the "hot spot" — of diameter d and area A_f.

$$d = \mathrm{a}\ \alpha \qquad A_f = \frac{\pi\ \mathrm{a}^2\ \alpha^2}{4} \qquad [1]$$

Referring to Fig. 2, we see that the focal plane images formed by reflection from all other points on the paraboloid (within the range of solar furnace design) will be ellipses. The ellipse formed at the focal plane by reflection from the point P will have the approximate minor and major axis diameters:

$$b_1 = \rho\ \alpha \qquad b_2 = \frac{\rho\ \alpha}{\cos\ \theta} \qquad [2]$$

The ratio E_θ between the hot spot area A_f and the ellipse area A_e will be found to be:

$$E_\theta \equiv \frac{A_f}{A_e} = \frac{\mathrm{a}^2 \cos\theta}{\rho^2} \qquad [3]$$

Now if we assume that the elliptical image is of uniform intensity (as it very nearly is, except at extremely large values of θ, then the fraction E_θ of the total radiant energy reflected from P will be directed to the hot spot.

We now consider the concentration ratio attained by a small ring-shaped portion of the paraboloid lying at an angle θ and bounded by the arc $d\theta$. (See Fig. 7.) The total solar energy per unit time falling upon this ring-shaped portion of the paraboloid will be the product of the incident direct sunshine intensity and the projected area of the ring-shaped portion:

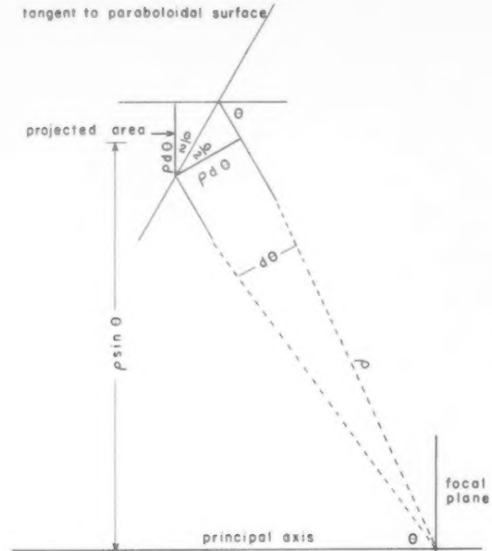


FIG. 7.

$$dQ = q_1 \, dA \qquad [4]$$

Inspection and consideration of Fig. 7 will show that this projected area dA is:

$$dA = 2\,\pi\,\rho^2 \sin\theta \, d\theta \qquad [5]$$

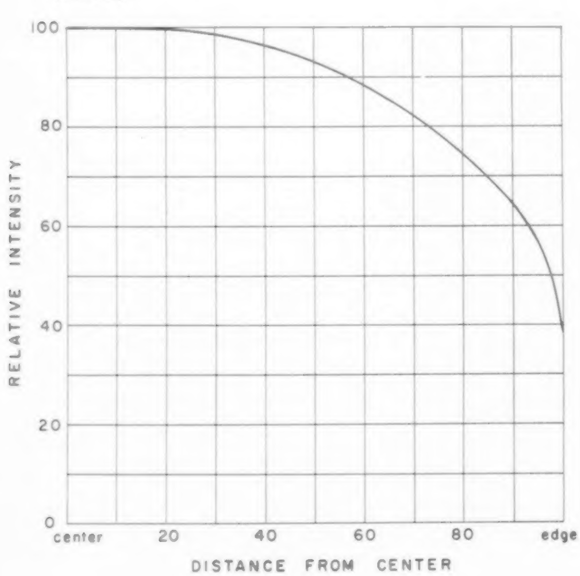
The fraction E_θ of the total energy dQ will be reflected to the hot spot. The resulting concentration ratio produced at the hot spot by the thin ring of the paraboloid will be:

$$dC = \frac{dq_t}{q_1} = \frac{E_\theta \, q_1 \, dA}{A_t \, q_1} \qquad [6]$$

Substituting from [1], [3], and [5] into the above will yield:

$$dC = \frac{8}{a^2} \sin\theta \cos\theta \, d\theta \qquad [7]$$

FIG. 8—Relative intensity of sunshine across the sun's disc (Abetti).



Integrating from the center of the paraboloid to rim angle θ_1 then gives the basic equation for the concentration ratio of a perfect paraboloid:

$$C = \frac{4}{a^2} \sin^2 \theta_1 \qquad [8]$$

The numerical results of this simple relation, but not the equation, have been worked out by Cabannes & Le Phat Vinh.[1] The equation itself is hidden in a complicated derivation by Farber & Davis.[2] Substantially the equation itself has been stated in recent papers by Duwez,[3] and by Benveniste & Hiester.[4] This equation is derived upon the following assumptions:

(1) The exact elliptical image diameters are given by Equation [2].

(2) The intensity of a given elliptical image is uniform over its surface.

(3) The sun's disc is of uniform intensity.

From the standpoint of the engineering accuracy of the basic concentration ratio equation [8], the inaccuracies contributed by assumptions (1) and (2) are of negligible importance even up to rim angles of 80°. This is a higher rim angle than would be practicable for a solar furnace. However, assumption (3), that the sun's disc is of uniform intensity, causes the basic concentration ratio to be slightly in error.

The sun's disc has a greater intensity at the center than at the edge. According to Abetti,[10] its intensity varies with radius somewhat as shown in Fig. 8. Our calculations from this curve indicate that the peak intensity at the center of the sun's disc is about 25 per cent greater than the average intensity of the disc. They also indicate that a perfect paraboloid of rim angle 60° should have a concentration ratio approximately 10 per cent greater than that given by the basic equation [8].

Insofar as an actual solar furnace is concerned, the effect of this limb-darkening is not necessarily in the direction of increasing the concentration ratio of the furnace over that which the furnace would have if the sun's disc were of uniform intensity. The limb-darkening phenomenon tends to increase any losses which may be present in the furnace as a result of geometrical imperfections of mirror surfaces. As a result, an actual solar furnace operating in actual (limb-darkened) sunshine may have either a a slightly higher or a slightly lower concentration ratio than it would have if the sun's disc were of uniform intensity. The exact magnitude of the effect is probably best determined by careful heat transfer tests made on furnace components prior to construction of a proposed furnace.

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FURTHER EVIDENCE OF INCREASED CARBON DIOXIDE PRODUCTION ACCOMPANYING PHOTOSYNTHESIS*

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Photosynthesis in tobacco and 8 other plant species was measured at varied illumination and CO_2 concentration. Measurements were made with an infrared gas analyzer in a closed recycling system. Curves of apparent photosynthesis vs light intensity and of apparent photosynthesis vs CO_2 concentration can be interpreted as demonstrating that CO_2 production was greater during photosynthesis than in the dark.

A rapid, short-lived outburst of CO_2 from green leaves immediately following darkening has been reported.[3] The outburst suggests the possibility of an increased production of CO_2 during photosynthesis. The experiments reported here provide further evidence of such an increase. Measurements of CO_2 production in the dark (dark respiration) were consistently less than estimates of CO_2 production during illumination. These estimates were derived from the curves of apparent photosynthesis vs light intensity and of apparent photosynthesis vs CO_2 concentration.

GENERAL METHODS AND MATERIALS

The apparatus used for measuring apparent photosynthesis was essentially a duplicate of one described earlier.[3] It consisted of a leaf chamber, a small air pump and an infrared gas analyzer (Liston-Becker model 15) in closed series. The analyzer gave a continuous indication of the CO_2 concentration of the system. Decreases in concentration were considered to show the amount of CO_2 taken up by the leaf, that is, the apparent photosynthesis.

The analyzer was calibrated as follows. Zero was set as the equilibrium reading obtained by recycling air through a system consisting of the analyzer, the pump, and a bubbling bottle of N/10 NaOH. The sensitivity control was then set so that a reference gas (compressed air containing approximately 300 ppm CO_2) gave a convenient reading, 70 per cent of full scale. Next a recycling system consisting of a 2000 ml flask, the analyzer, pump, and NaOH bubbler was set up and run for 30 minutes. The bubbler was removed and the system was run for several minutes to test for last traces of CO_2 (in preliminary work it was found that although a briefer scrubbing took the system down to zero CO_2, traces appeared during the subsequent blank cycling). A preset syringe and 22 gauge needle were used to inject 0.2243 ml of CO_2 directly into the closed system through thick-wall rubber tubing. The volume of the system was 2242 ml; thus, injections increased the concentration of CO_2 in steps of 100 ppm. The calibration curve was slightly curvilinear ($Y = 0.3X - 0.0002X^2$, where Y is the meter reading between 0 and 100 microamperes and X is the CO_2 concentration between 0 and 500 ppm.) Corrections were calculated for intervals of 1 microampere.

Although the analyzer was slightly sensitive to water vapor (the difference between readings for dry and saturated nitrogen was equivalent to 15 ppm of CO_2), the measurements of changes of CO_2 concentration were probably free of error due to changes in humidity because the system remained constantly saturated or nearly so. The greatest change in humidity was expected to result from a change in leaf temperature during a dark-light cycle, but a simple test showed no detectable change. This test was made by substituting a piece of moistened black cloth for the leaf and observing the reading of the analyzer through repeated cycles of dark and light.

The routine operating procedure was as follows. A leaf, still attached to the plant, was sealed in the chamber and left (with the system closed and operating) for 30 minutes at 25°-26° and a predetermined light intensity before measurements were begun. Then a tubing connection was opened, an excess of CO_2 was added and the system was reclosed. The fall of CO_2 concentration over a predetermined range was timed with a stop watch. Measurements were replicated as needed.

Dark respiration was measured after all other measurements were completed and after the leaf had been in the dark for at least 10 minutes. Before the measurement was begun, a NaOH bubbling bottle was inserted in the system to reduce the concentration of CO_2. The rise of concentration was timed over the same range used for the preceding photosynthesis measurements.

The plants, a hybrid tobacco (*Nicotiana langsdorfii* x *N. sanderae*), were grown in a greenhouse under natural light. They were planted December 15, 1954. Studies reported here were made during March 1955. Only dark green, fully developed leaves were used. Leaves were

* The experimental work was done at the Brooklyn Botanical Garden.

** Central headquarters maintained in co-operation with Colorado A & M College at Fort Collins, Colorado; author stationed at Tempe, Arizona, in co-operation with the University of Arizona and Arizona State College.

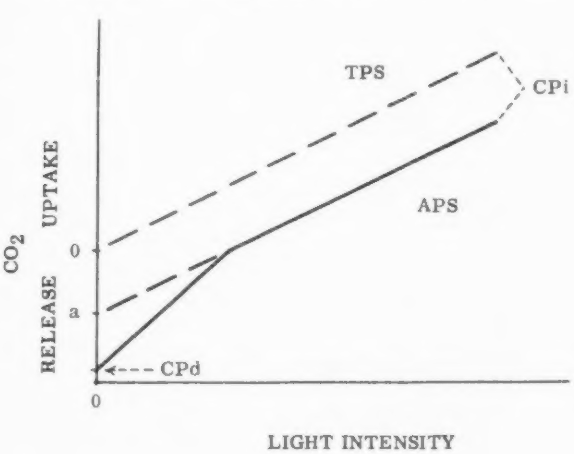
longer than the leaf chamber and were cut to fit. To test the effect of the cutting, a truncate leaf was sealed in the chamber; quintuplicate measurements were made of apparent photosynthesis; the chamber was opened; the leaf was slit bilaterally from margin to midrib at the widest part of the blade; the chamber was resealed; and quintuplicate measurements were again made. This procedure was followed with six leaves. There was no detectable difference between measurements made before and after slitting. Because the experimental slitting more than tripled the amount of cut edge exposed in the chamber yet produced no measurable effect, the preliminary trimming was assumed to have no effect. Further, all leaves were trimmed and, within any experiment, all leaves received all treatments, thus any hidden consistent effect of the trimming would be cancelled.

Leaf area was calculated from the weight of a piece of heavy aluminum foil that had been cut to match the leaf. The leaf was flattened on the foil blank and stapled to hold it firmly while the foil was cut.

APPARENT PHOTOSYNTHESIS VS LIGHT INTENSITY

According to Bonner and Galston[2] it is commonly assumed that true photosynthesis exceeds apparent photosynthesis by CO_2 production equal to respiration in the dark. If this assumption is true and if true photosynthesis is a linear function of light intensity, at least near the compensation point, the curve of apparent photosynthesis vs light intensity should pass smoothly through the compensation point with no change in slope. However, van der Veen,[5] who studied the uptake of CO_2 by tobacco leaves, found a change of slope at or near the compensation point, with the lower segment markedly steeper (the so-called Kok-effect). Because the upper segment extrapolated to a value less than dark respiration, he interpeted his results as indicating that respiration in the light was less than respiration in the dark.

FIG. 1—Diagrammatic representation of apparent photosynthesis (APS) as a function of light intensity and showing its hypothetical relationship to true photosynthesis (TPS) and to CO_2 production during illumination (CPi). CO_2 production in the dark is designated at CPd.



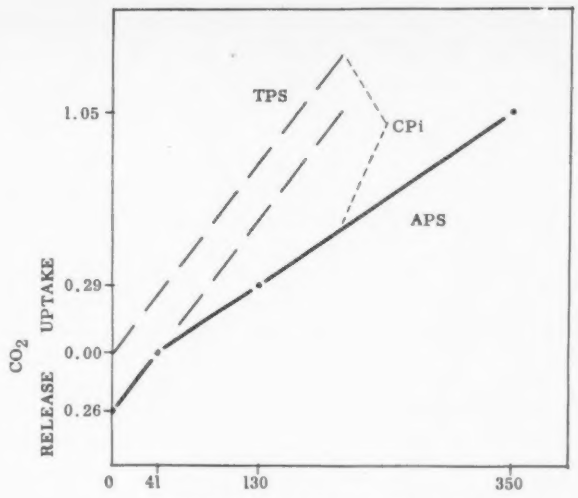


FIG. 2—The effect of light intensity on apparent photosynthesis (APS) of tobacco leaves at 300 ppm CO_2 and 25°-26° C, and the relationship of APS to a hypothetical true photosynthesis (TPS) such that CO_2 production during illumination (CPi) appears greater than respiration in the dark. Confidence range shown is 5 per cent tse (t x s.e.). Ordinal unit: μg CO_2 per second per dm^2 of leaf area.

As shown in Fig. 1, his interpretation required the tacit assumption that the curve of true photosynthesis is linear, passes through 0,0 and is parallel to the upper segment of the curve for apparent photosynthesis. A second possible interpretation is that CO_2 production in the light was equal to that in the dark. This requires the assumption of a change of slope of the curve of true photosynthesis paralleling the curve of apparent photosynthesis. A third possible interpretation, that CO_2 production was greater in the light than in the dark, is shown graphically in Fig. 2. This requires the assumption that the curve of true photosynthesis is linear and parallel to the lower segment of apparent photosynthesis. CO_2 production would be constant from zero light to the compensation point and would increase uniformly with greater illumination.

Because van der Veen's work was exploratory, the following experimentation was undertaken to retest his findings. Routine operating procedures were followed. Apparent photosynthesis was measured over a CO_2 concentration interval that had its midpoint at 300 ppm and represented an uptake of $100 \mu g$ by the leaf. Five measurements were made alternately at each of the two intensities (350 fc, 130 fc). Light screens were then added until the compensation point was reached, that is, until the CO_2 concentration remained constant at 300 ppm. Only single observations of the compensation point were made because preliminary tests showed it to be remarkably constant, that is, successive trials with the same leaf always were identical whether made a few minutes or 3 hours apart, provided temperature was the same. The observations were tested further, however, by observing the slow drift of CO_2 concentration at the next higher and

lower steps of light intensity. The overall accuracy of the observations was limited by the reliability of the light meter (a General Electric DW-68) and the uniformity of illumination (e.g., when illumination was 50 fc at the center of the leaf it was 45 fc at the edges). As the next step in the routine procedure the leaf was left in the dark for at least 10 minutes and triplicate measurements were made of dark respiration. The whole procedure was repeated with two more plants.

The results (Fig. 2) appear very similar to those of van der Veen and can be interpreted as indicating that CO_2 production in the light may have exceeded that in the dark. However, the other two possible interpretations cannot be ruled out, and thus additional and independent tests are needed. One such test was possible through a study of the effect of CO_2 concentration on apparent photosynthesis. It is described below.

APPARENT PHOTOSYNTHESIS VS CO_2 CONCENTRATION

The effect of CO_2 concentration on apparent photosynthesis has been studied extensively, and the work has been reviewed recently by Bonde[1] and Steeman-Nielsen.[4] Because available data in the very low range of CO_2 are inadequate, the following study was undertaken. The plants and general procedure were the same as in the preceding study. Light intensity was 2500 fc throughout. The fall of CO_2 concentration was timed over short intervals having midpoints at 400, 300, 200, and 100 ppm. Three such runs were made and then the CO_2 was allowed to fall to a stable compensation point. The reading was considered stable if it remained unchanged for 5 minutes (preliminary tests showed that if there was no perceptible change in 5 minutes there was none in 60 minutes). The series consisting of triplicate measurements of apparent photosynthesis at each concentration and one measurement of the CO_2 compensation point was done five consecutive times. Then the leaf was left in the dark for at least 10 minutes and duplicate measurements were made of respiration. The whole procedure was repeated with two more plants.

A summary of the observed values for apparent photosynthesis is given in Fig. 3. Dark respiration was 0.27 μg CO_2 per second per dm^2 (mean of six observations). The curve resembles that shown by Bonde.[2] An enlarged view of the lower segment is shown in Fig. 4.

That the results suggest an increase of CO_2 production during photosynthesis becomes evident upon considering a hypothetical situation in which there is no direct reuse of endogenous CO_2. Photosynthesis would depend entirely on external CO_2, and true photosynthesis would become zero at zero CO_2 (Fig. 4, curve 1). Apparent photosynthesis would differ from true photosynthesis by the amount of endogenous CO_2 that leaked into the external system. Extrapolating apparent photosynthesis to zero CO_2 would yield an estimate of this leakage. If all endogenous CO_2 leaked and if CO_2 production in the light equaled that in the dark, apparent photosynthesis should be as curve 2 (Fig. 4), with the extrapolated value equaling dark respiration. The fact the value extrapolated from

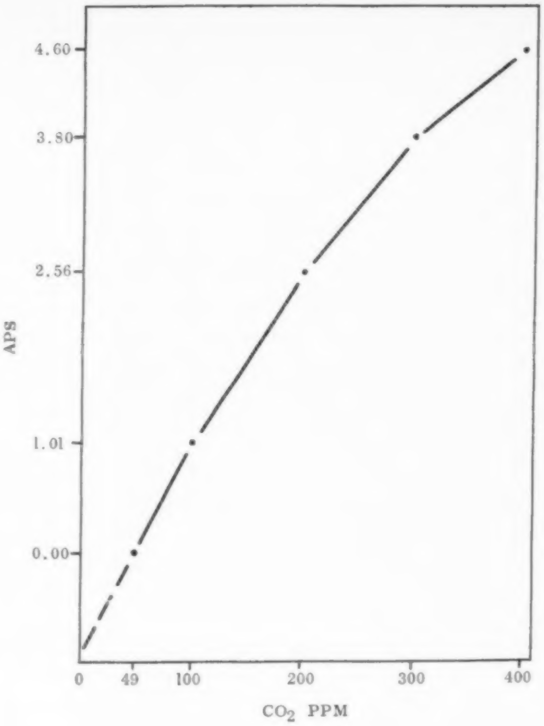
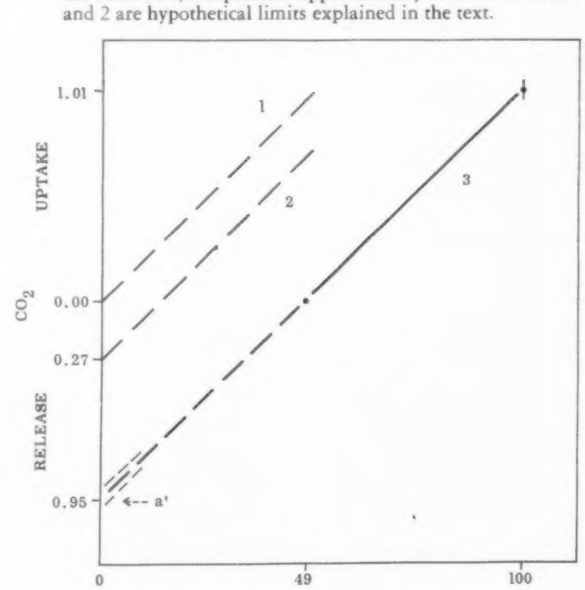


FIG. 3—The effect of CO_2 concentration on apparent photosynthesis of tobacco leaves at 2500 fc and 25°-26°C. Each upper point is the mean of 45 observations. The CO_2 compensation point (APS = 0) is the mean of 15 observations. Ordinal unit: μg CO_2 per second per $dm.^2$

FIG. 4—Curve 3 is an enlarged view of the lower segment of Fig. 3. Confidence range for the upper point is 1 per cent tse. 1 per cent tse for the compensation point is included within the dot. Confidence range shown for the extrapolated value (a′) was obtained by extending the opposite extremes of the other two, it represents approximately 0.01 tse. Curves 1 and 2 are hypothetical limits explained in the text.



the experimental data (Fig. 4, curve 3) is 3.5 times greater ($0.95/0.27 = 3.5$) indicates that CO_2 production in the light was at least this much in excess of dark respiration.

The indicated excess is a minimum limit — an estimate that assumes no direct reuse of endogenous CO_2. The actual excess was probably greater, for there probably was some direct reuse but the amount cannot be determined from this experiment.

Several additional facts concerning the experimental method should be mentioned. The assumption is made that respiration was not affected appreciably by changes in CO_2 concentration. Although this independence was not tested in the present work, it was demonstrated with the same kind of plants in earlier work.[3] The leaves were exposed to unnaturally low CO_2 concentrations, but preliminary tests showed such exposure to have no effect on subsequent measurements of photosynthesis. In these preliminary tests a leaf was held at 300-500 ppm CO_2 prior to the first measurement of photosynthesis. Then the CO_2 concentration was held at the compensation point for a period ranging from a few seconds to an hour, and photosynthesis was remeasured.

STUDIES ON OTHER SPECIES

To determine whether the apparent increase of CO_2 production accompanying photosynthesis is peculiar to tobacco, several other kinds of potted greenhouse plants were studied. These included white ash *(Fraxinus americana)*, tuliptree *(Liriodendron tulipifera)*, geranium *(Pelargonium* sp.), grapefruit *(Citrus paradisi)*, foxglove *(Digitalis* sp.), common poinsettia *(Euphorbia pulcherrima)*, a fern *(Selliguea caudiforme)*, and ginkgo *(Ginkgo biloba)*. Three plants of each species were used. General operating procedure was the same as with tobacco. The sequence of measurements with each plants was as follows: (1) triplicates of apparent photosynthesis at 1400 fc and 100 ppm CO_2; (2) CO_2 compensation point; (3) triplicates of apparent photosynthesis at 180 fc and 300 ppm; (4) light compensation point; (5) duplicates of dark respiration; (6) leaf area.

Results are shown in Table 1. The algebraically extrapolated values corresponding to those shown in Figs. 1 and 4 are listed under columns *a* and *a'*. Respiration was consistently greater than *a* and less than *a'*, thus CO_2 production during photosynthesis appeared to exceed dark respiration in all species.

TABLE I

Apparent photosynthesis in μg CO_2 per second per dm^2 at 180 fc and 300 ppm CO_2 (APS_1) and at 1400 fc and 100 ppm (APS_2), the CO_2 compensation point in ppm (CCP), the light compensation point in fc (LCP), and production in the dark in μg per second per dm^2 (CPd).

	APS_1	APS_2	CCP	LCP	CPd	*a*	*a'*
Fraxinus americana	0.398	0.572	51	34	0.170	0.09	0.595
Liriodendron tulipifera	0.384	0.610	57	35	0.199	0.09	0.809
Pelargonium sp.	0.350	1.22	51	67	0.411	0.21	1.27
Citrus paradisi	0.418	1.04	50	52	0.251	0.17	1.04
Digitalis sp.	0.212	0.974	53	112	0.525	0.35	1.11
Euphorbia pulcherrima	0.266	0.963	51	63	0.380	0.14	1.01
Selliguea caudiforme	0.338	0.328	60	23	0.103	0.05	0.492
Ginkgo biloba	0.465	0.914	52	25	0.202	0.08	0.991
Standard error ±	0.031	0.059	2.2	4.6	0.023		
Number of observations per entry	9	9	3	3	6		

The author is indebted to Dr. J. L. Kovner for suggesting the second interpretation of van der Veen's work.

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APPLICATION OF SOLAR ENERGY TO SMALL SCALE INDUSTRIES

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An important field of utilization for solar energy in India is in small village industries, as a supplementary power source. The application of solar energy to the raising of water for irrigation and domestic purposes, to cooking and to power generation are here discussed briefly; and the concentration of sugar cane juice and palm juice examined in some detail. Results are tabulated for experiments on the evaporation of cane and palm juices conducted in the Laboratory and in the open fields, using solar concentrators with 9 in. square plane mirrors, designed by Gardner. Field experiments showed an efficiency of 30 per cent, but it should be possible to reach 50 per cent. The capital cost of the unit can be recovered in fuel savings within 3 seasons.

GENERAL CONSIDERATIONS

Considerable importance is attached in India to the development of small scale industries. In a country having a large population and comparatively limited industrial development the question of providing employment to people is of paramount importance. The Planning Commission of the Government of India is thinking in terms of finding sources of employment for some twelve million people. It is, therefore, necessary that for providing gainful employment to this large number of people the role of small scale industries should be fully exploited. One of the great handicaps to this development has been the non-availability of power to the rural population. India has very limited petroleum resources of its own and the cost of imported liquid fuels makes their use uneconomical. Coal is available, but its distribution over long distances and in remote villages raises problems of transportation. The problem can be solved to some extent if solar energy could be made available for at least some of the village industries to supplement the present resources.

Indian villages need power for some of the following uses:

(1) raising water from wells for irrigation and domestic purposes;

(2) heat for cooking;

(3) power for cottage industries, e.g., palm-jaggery making, timber seasoning, drying of some agricultural produce.

WATER FOR IRRIGATION

Requirements for small scale irrigation and domestic purposes should be well within the means of solar energy to meet though here, as an alternative, wind power can also be used, especially some of the newer models of windmills developed for low-wind regions.

Large stretches of Indian countryside are dotted over with irrigation wells which are worked mostly by bullocks. A pair of bullocks working continuously can raise about 800 gal of water per hour from a depth of 30 ft or so. The equivalent of this work can be done by an electric motor pump rated at 0.8 kw. Taking a working period of 8 hours, the daily output of two bullocks will come to between 6000 to 6500 gal, equivalent to less than 20¢ at the prevalent cost of electrical energy. Thus from point of view of irrigation alone, the work of one bullock is equivalent to less than 10 cents per day. We are neglecting here the cost of an attendant since it is the farmer himself who acts as the bullock-man while his wife or children receive the buckets of water as they come up and help in the diversion of water into channels. It would appear from the above that the use of bullocks for drawing water is highly uneconomic and only continues because of the want of an alternative. In a paper presented by the present authors before UNESCO Symposium on Wind Power and Solar Energy this aspect was discussed and a suggestion was made that for India this will be a most desirable field, where a direct method of utilization of either solar energy or wind power could be most fruitful. During the year, we have been studying the possibility of using hot air engines as prime movers, the heating of the engine being done by mirror concentrators designed by Gardner[1] at the National Physical Laboratory of India. We have under investigation a hot air engine developed at Eindhoven. The model under test has a coupled generator capable of a maximum of 200 watt output. The heater system of this engine is designed for burning kerosene oil and is in the form of a cylindrical head of 8 cm diameter with an exposed surface area of 50 sq cm. The kerosene burner was removed and suitable metal plates were placed to intercept the reflected energy from a solar concentrator and transfer it to the head. The engine could be made to run at its rated capacity.

HEAT FOR COOKING

Solar energy can be only partially used for this purpose. Since tradition in cooking methods plays a very major part, it is doubtful if much could be done yet in changing the traditional methods of cooking either in villages or in cities. In regions where firewood is not available, dried cow dung made in the form of flat cakes is generally used. Efforts made to introduce solar cookers in villages have completely failed. In cities their use is impracticable on account of limitation of sunlit space.

POWER FOR COTTAGE INDUSTRIES

So far the cottage industries have been almost entirely worked with manual power. With the increasing cost of labor and a growing consciousness for larger output, various types of mechanical devices are being introduced

in cottage industries. This is most noticeable in improvements made in spinning wheels and hand-looms to make them semi-automatic. Industries like hosiery knitting are run mainly on cottage industry lines but these are mostly concentrated in cities where electric power is available for working small motors. A large proportion of the sports goods industry is run on cottage industry lines and so also are numerous minor industries such as sewing machine and bicycle parts. The role, therefore, of small scale industries in providing employment in villages and incidentally in stopping migration of people to towns is of great importance to the economy of the country.

A small scale industry in which solar energy could be extensively used is making jaggery from palm juice, and we propose to discuss it here in greater detail.

PALM JUICE CONCENTRATION

The importance of the application of solar heating to palm juice concentration arises from the fact that the region where palms are most common is devoid of locally available fuels and the cost of transportation of coal is high. Unlike the sugar cane where bagasse can be used as fuel the palm trees do not supply any by-product which can be used as fuel material.

The palm tree can be grown over most parts of India. In the moist coastal regions the palmyra and coconut and sago palms grow vigorously. In the dry and hot regions the date and to some extent palmyra thrive well. All the palm varieties share the common habit that they can thrive on waste lands on which nothing else will grow.

On a rough computation[2] there are approximately 200 million palm trees in India in which the number of coconut trees outstrips the rest of the varieties added together. The palm trees are tapped for juice at a point near the crown in a somewhat similar manner as the rubber trees are tapped for latex. During a tapping season each tree yields between 5 to 15 lb of juice per tapping, depending on the variety. The juice thus collected is evaporated to a solid jaggery which is commonly known as "gur". From this, white sugar can be made by refining, but the gur replaces sugar in the village economy and has higher vitamin and mineral content. The yield in lbs of gur per tree during a season is somewhat as follows:

	Date	Palmyra	Coconut	Sago
Maximum	50 lb	150 lb	80 lb	400 lb
Minimum	15	40	60	200
Average	25	60	70	300

A simple calculation shows that the palm trees if fully utilized are capable of providing between 5 to 10 million tons of jaggery or unrefined sugar of high mineral and vitamin content. However, the current production of solid gur is only about 60,000 tons. From actual trial experiments it has been estimated that a field of one acre planted with palm trees could produce yearly about 8,000 lb of sugar and that in a soil quite unfit for any other kind of culture. The only drawback in such kind of plantation is that the tree must be eleven or twelve years old before it will yield sugar. This is, however, counterbalanced by its long useful life extending up to 90 years or so for the palmyra.

One of the greatest difficulties with palm juice is that it cannot be kept for any length of time. In fact it starts fermenting even as it is being tapped and requires an antacid like lime to be added to the collecting pots to prevent progressive fermentation. It becomes necessary, therefore, that means for concentrating the juice be available right in the collecting area itself since transport over any distance is out of question. The use of solar energy for heating palm juice can, therefore, solve the difficult fuel problem and offer, incidentally, a possibility of extending tapping over large arid areas where date palm and palmyra can be easily grown. In most of the arid palm growing areas clear sunshine is available through the tapping period, which is about six months in the case of date and palmyra and can be throughout the year in the other two varieties.

On an average a carefully designed coal furnace requires 25 lb of steam coal for evaporating 100 lb of juice yielding about 12 lb of jaggery. On the present target of production the annual output of palm gur should go up to 100,000 tons, which will require 208,000 tons of coal. On the basis of the figures available from the various production units, the average cost of fuel including some of the agricultural wastes comes to 2/8 rupees or slightly over 50 cents per 100 lb of jaggery. Hence for 100,000 tons of palm jaggery the total saving on fuel will come to 5½ million rupees, equivalent to well over one million dollars.

EXPERIMENTAL

Experiments on evaporation of cane and palm juices were conducted both in the Laboratory and in actual fields. Solar concentrators using 9 in. square plane-mirrors prepared in the Laboratory by Gardner[1] were used in all the experiments. Preliminary experiments on evaporating water from a shallow tray measuring 18 in. by 18 in. gave the results shown in Tables I, II and III.

The above experiments were carried out at a village in Bombay State in collaboration with the Palm Gur Technological Institute of Dhanu. The evaporating pans used in the field trials were the same as commonly used in villages. The major source of heat loss in the above experiments was high wind velocity. The high prevailing humidity also tended to reduce evaporation. The improvised furnace, too, was far from efficient. A simple calculation shows that in the field experiments the percentage utilization was about 30 per cent, against a safe value of about 45 per cent for cane juice and somewhat higher for water using open pans and making no provision to shield from winds. With properly constructed furnaces and provision made for shielding the boiling pans from direct wind, it should be possible to improve the efficiency to about 50 per cent.

If we select for development a unit making, say, 36 lb of gur per day, the quantity of juice to be handled will come to about 30 gal. At 45 per cent efficiency the area of mirror surface required will be 330 sq ft (reckoning 8 hr per day working and taking 25 Btu per hr per sq ft as direct solar intensity). This work could be conveniently

handled by two furnaces each using 165 sq ft mirror surface and producing 18 lb jaggery. In the reflectors we have been trying out, the focus is adjusted to about 20 ft distance. Here 8 reflectors of 3 ft width are about the maximum that can be used. Gardner,[1] however, thinks that it will be advisable to increase the focal distance to 25 ft and use reflectors measuring 5 ft high by 4 ft wide thus giving a mirror surface of 20 sq ft per reflector. Eight such reflectors can thus be conveniently grouped around one furnace. This will leave sufficient space for addition of an extra frame or two in case of difficult weather conditions.

Cost: Each frame of 5 ft by 4 ft will cost approximately 21 rupees ($4.41). Hence each heating unit will cost 168 rupees ($35.28) with a reserve of 50 rupees ($10.50) for two extra frames and some spare mirrors. On the present figures available which take account of steam and some forest wastes, the fuel cost per 15 gal unit will be 12 rupees ($2.52) per day. On a 90-day working the saving in fuel will amount to 67/8 rupees ($14.18). The unit can, thus, recover its capital cost within three seasons. In coconut areas the tapping season lasts about 6 months, from January to June, which is also the period when bright sunshine will be available during almost the entire period. On the above calculation the cost of the reflectors will be recovered in 1½ coconut seasons.

The authors acknowledge with thanks the collaboration and help received by them from the Director, All India Palm Gur Technical Institute, Dhanu, Bombay, to conduct at his Institute the experiments on the concentration of palm juice reported in this paper.

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TABLE I: EVAPORATION OF WATER FROM A SHALLOW PAN

Ambient temperature: min. 60°F; max. 74°F.

Mirrors: 6 frames of 7.0 sq ft each

No.	Date December 1954	Loss in weight in lb	Initial temp. of water	Time in hours From	To	Total solar energy in Btu (corrected)	Average per cent efficiency	Remarks
1	21st	16.84	17°C	11.15	16.15 (5 hr)	42890	44	
2	22nd	28.40	13°C	09.30	16.30 (7 hr)	58480	55	
3	23rd	25.88	14°C	10.15	16.45 (6½ hr)	56390	52	
4	24th	15.40	14°C	10.00	16.30 (6½ hr)	38160	41	
5	27th	20.76	15°C	10.00	16.30 (6½ hr)	47120	49	

Note: The difference in efficiency may be due to the fact that the position of mirrors requires frequent adjustment due to change of sun position.

TABLE II: EVAPORATION OF SUGAR CANE JUICE FROM A SHALLOW PAN

Ambient temperature: min. 60°F; max. 72°F.

Mirrors: 6 frames of 7.0 sq ft each

No.	Date December 1954	Loss in weight in lb	Initial temp. of water	Time in hours From	To	Total solar energy in Btu (corrected)	Average per cent efficiency	Remarks
1	28th	21.83	17.5°C	10.15	16.00 (5¾ hr)	44930	54	
2	29th	20.03	14 °C	10.00	15.45 (5¾ hr)	55510	41	
3	30th	19.39	13 °C	10.00	16.30 (6½ hr)	55400	39	

Note: Cane juice was reduced to a semi-solid mass which on cooling set to solid jaggery.

TABLE III: EVAPORATION OF PALM JUICE

Ambient Temperature: max. 88°F.

Solar energy: approx. 11000 Btu per hr

Humidity: 78 to 80 per cent Mirror: 8 frames of 7 sq ft each

No.	Date May 1955	Initial wt of palm juice in lb	Wt of water evaporated in lb	Quantity evaporated in lb per hr	Time in hr	Remarks
1	26th	20	15.3*	2.2	7	Clear day with occasional clouds
2	27th	25	22	3.66	6	Clear day with occasional clouds
3	29th	32	28	4.0	7	Clear day
4	30th	50	34½*	4.14	8⅓	Clear day
5	31st	41	31 *	3.87	8	Cloudy towards morning and afternoon

Values marked * are for thickened syrupy fluid which would require further concentration.

THE MASS CULTURE OF ALGAE

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A pilot plant scale apparatus for the mass culture of algae is described which gave trouble free operation over a period of almost a year. Algal growth rates obtained in this equipment compare favorably with those reported elsewhere with a maximum rate of 14.4 gm of dry *Chlorella pyrenoidosa* per sq meter per day being achieved.

Consideration is given to many of the limitations imposed by nature which must be successfully overcome before the mass culture of algae can be considered economically feasible on an industrial scale. A very rough estimate shows that the cost of algae under even extremely favorable conditions would be at least 50 cents per pound.

The authors feel the mass culture of algae will not be economically practical as a source of foods or feeds until some major research "break-through" occurs.

INTRODUCTION

During the last two years the subject of the mass culture of algae has evoked considerable interest in the scientific and popular press. This interest is centered around the large potential of algae as: (1) a possible human or animal food which could be grown economically in large quantities on a relatively small area; (2) a means of storing the energy of sunlight for subsequent use.

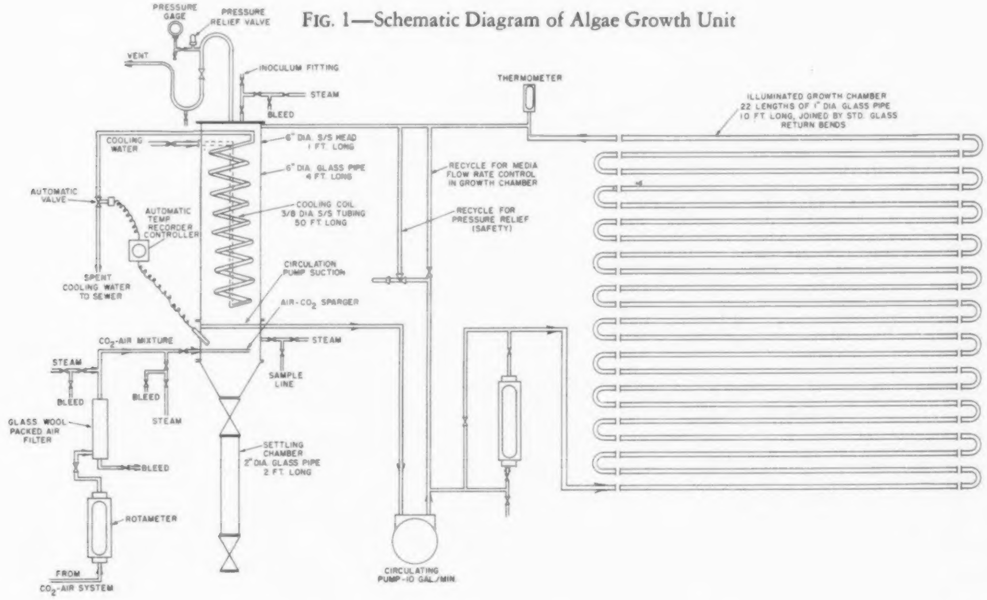
However, as pointed out by Paul Cook,[8] in developing a process for the large scale culture of algae, it is necessary to study first the limitations imposed by nature. Within these parameters a process must be developed which will economically produce organic matter. There is actually no need to study the other aspects of the problem until it can be shown that these natural limitations do not *per se* condemn the process to economic failure.

It is, therefore, the purpose of this report to describe briefly our own experimental equipment, present a few of our results, and to point out some of the natural limitations which it is believed must be overcome prior to the successful and economical mass culture of algae.

Many of the prime aspects of the mass culture of algae have been discussed. Consideration has been given to:

(1) energy requirements for photosynthesis,
(2) turbulence requirements of media,
(3) carbon dioxide requirements and sources,
(4) other possible carbon sources,
(5) nitrogen requirements and sources,
(6) other major nutrient requirements,
(7) micro-nutrient requirements,
(8) absolute maximum rate of photosynthesis of algae,
(9) temperature and refrigeration requirements,
(10) sterility,
(11) growth inhibiting excretory products,

FIG. 1—Schematic Diagram of Algae Growth Unit



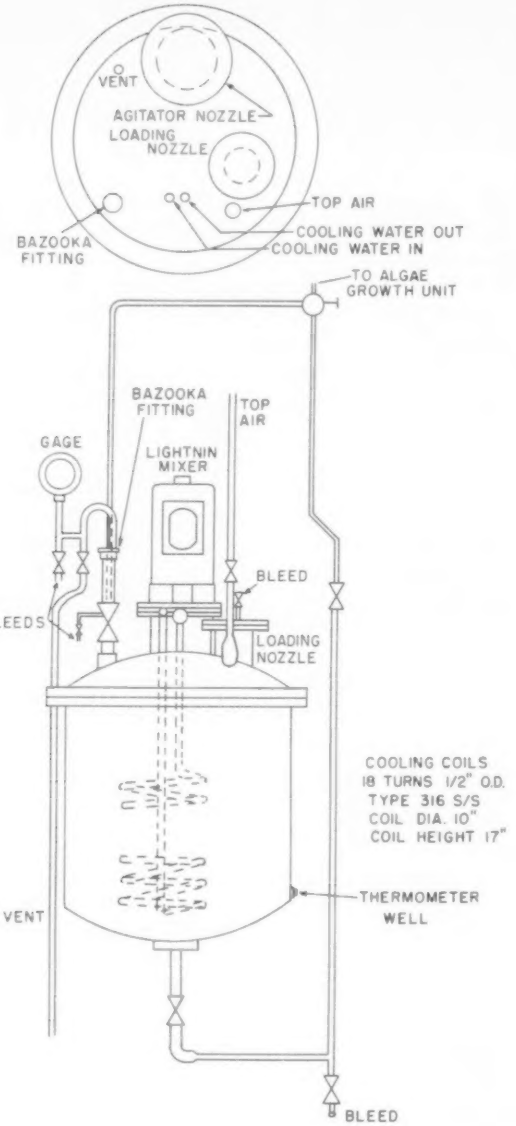


FIG. 2—Media Preparation Tank

(12) the "theory of the optimum catch",
(13) cost.

A very rough estimate shows that the cost of algae under extremely favorable circumstances would be at least 50 cent per pound. At this cost algae cannot compete with products already on the market, such as soy beans, corn, wheat, etc.

Our pilot plant data which closely parallels the best reported to date indicates that the large scale culture and recovery of algae for use as food or feeds is not now economically feasible and will not be economically practical unless some unusual research break-through takes place.

This paper sets forth the hard facts that must be overcome for successful solution to this problem.

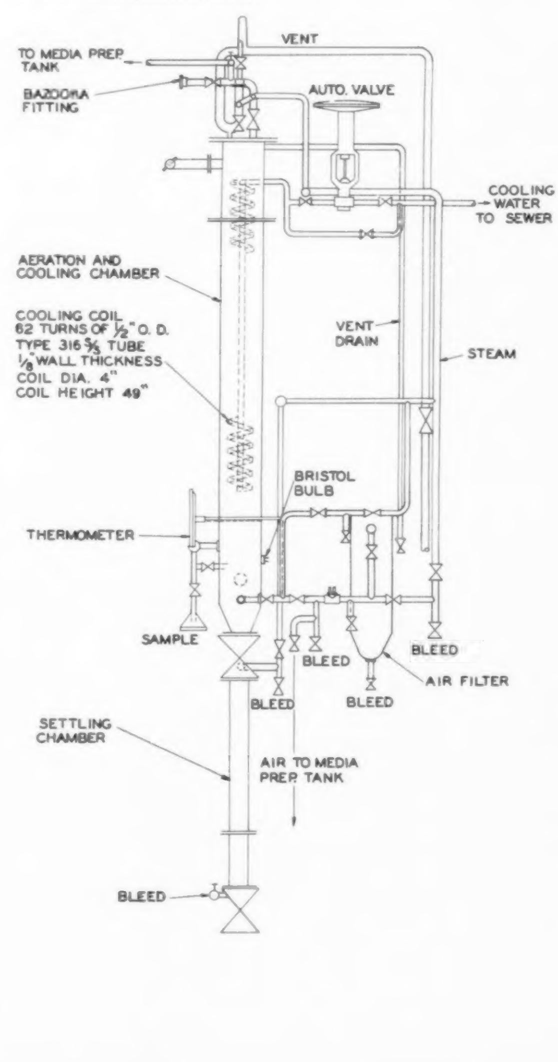
EXPERIMENTAL

After a survey of the literature a pilot plant for the study of the mass culture of algae was designed and constructed. The unit consisted of the following:

(1) Inoculum preparation equipment including a slant culture cabinet and a rotary shaker;
(2) The growth unit itself which is shown schematically in Fig. 1 and consisted of:
  (a) a media perparation tank (Fig. 2)
  (b) the aeration system
  (c) the cooling system
  (d) the aeration and cooling chamber (Fig. 3)
  (e) the growth chamber (Fig. 4)
  (f) the lighting system
(3) The recovery equipment composed of a super centrifuge and a freeze dryer.

The slant culture cabinet was merely a bank of shelves, each lighted with fluorescent tubes, and placed in a cool room. Light intensity at the shelf surface was 250 foot candles. Here various uni-algal cultures were cultivated on a suitable sterile agar media in 1 in. by 6 in. culture tubes plugged with non-absorbent cotton.

FIG. 3—Algae Growth Unit: Aeration and Cooling and Settling Chamber (Sheet No. 2)



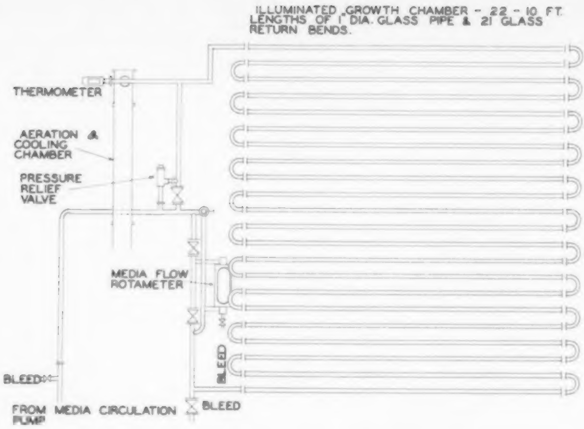


FIG. 4—Illuminated Growth Chamber

Inoculum for the unit itself was grown up in Fernbach flasks on a constant temperature rotary shaker equipped with fluorescent tubes, a heating system, and a cooling system. Twenty-five of the agar slants previously described were each harvested with 10 cc of sterile water each. These harvests were combined and used to innoculate 1500 milliliters of suitable sterile aqueous media in each of twelve 2800 milliliter Fernbach flasks.

The flasks were placed on the shaker, illuminated, and aerated with a mixture of carbon dioxide and air. The air was sterilely filtered prior to use. The aeration rate was determined by a rotameter, and the desired temperature maintained by use of an automatic temperature controller-recorder. Light intensity was 500 foot candles. Growth was followed visually and by means of periodic cell counts on samples removed. The flasks were allowed to incubate until growth was complete. This usually required 5-15 days.

At the end of this period the flasks were taken from the shaker, a sample was removed from each, and the flasks were stored at 4°C and the cells allowed to settle. While this settling process was going on, the samples were checked for the presence of foreign organisms by means of microscopic examination, and incubation at 37°C in nutrient broth and on beef lactose agar. Contaminated flasks were discarded.

After the cells had settled, the supernatant liquor was poured off the cells in the Fernbach flasks using aseptic techniques and working under a sterile hood. The concentrated cell suspensions in each flask were combined and this suspension was used to inoculate the unit itself.

Media for use in the algal growth unit was prepared and heat sterilized in the media preparation tank (Fig. 2). This was a 50 gal, stainless steel vessel equipped with an agitator and cooling coils. Prior to loading, this tank was washed with acid, thoroughly water rinsed, and autoclaved. Media was then loaded into the tank and autoclaved at 20 lb per sq in. gauge pressure. This sterile media was then transferred to the algal growth unit itself by means of sterile air pressure.

The algal growth unit could be considered to consist of the aeration and cooling chamber (Fig. 3) and the illuminated growth section (Fig. 4). The aeration and cooling chamber was made from a 4 ft length of 6 in. diameter, "double tough" Pyrex glass pipe mounted as a vertical column. This glass column was fitted at both top and bottom with a 1 ft length of 6 in. diameter stainless steel pipe. Through these metallic sections all entries, such as air lines, cooling water lines, steam lines, media loading lines, sampling lines, vents, thermometers, thermocouples, pressure gauges, media circulation lines, and other necessary fittings were made.

This column was fitted with a 4 in. diameter stainless steel cooling coil with an overall height of 4 ft. Water was used as the coolant. The flow of the cooling water was regulated by an air actuated automatic valve, which was controlled by an automatic temperature recorder-controller, actuated by a thermocouple placed in the media.

A mixture of carbon dioxide and air was used to aerate the media. These were mixed automatically in the desired proportions in a surge tank.[6] The mixture was sterilized prior to use by the usual methods.

The aeration mixture entered the bottom of the aeration and cooling column and was distributed as small bubbles by means of a perforated pipe sparger.

A small portion of the gas mixture bubbled up through the column of media and passed out through an inverted U-gooseneck vent. By far the largest percentage of the gas mixture traveled concurrently with the media through the illuminated growth section, returned to the top of the aeration and cooling chamber with this media, and then exited from the system through this same vent.

The illuminated growth section (Fig. 4) consisted of approximately 240 ft of 1 in. diameter "double tough" Pyrex glass pipe. This was arranged in a bank of 22 lengths of 10 ft pipe connected with standard return bends, each length mounted above the other on 5½ in. centers. The volume of this section was approximately 38 liters and the inside surface area 62.5 sq ft or 5.81 sq m.

The media was circulated from the bottom of the aeration and cooling chamber, through the growth chamber, and back to the top of the aeration and cooling column by means of a rotary pump. This pump was a positive displacement type and took its suction through an "umbrella-like" arrangement placed immediately above the aeration sparger in the aeration and cooling column. Thus a large portion of the carbon dioxide air mixture was pumped along with the media itself and also made the journey through the illuminated growth chamber. Because of the presence of the 21 return bends mounted in a vertical plane, contact between gas and media was intimate and mixing believed to be thorough. A by-pass around the growth chamber was provided so that the media flow rate in this section could be varied.

The growth chamber was illuminated by means of 120 fluorescent tubes. These tubes were 48 in., 40 watt, standard cool white. They have a lighting efficiency of slightly less than 10 per cent. The spectral distribution shows a spread in the visible range between 350 and 750 mμ with

a preponderance of visible light between the wave lengths of 550 to 650 mμ. The fluorescent tubes were mounted about 9¾ in. from the center line of the glass pipe. The glass pipe was backed up with a plywood panel painted with high-gloss white enamel. Thus, the glass pipe, which constituted the growth chamber, was mounted in a "corridor" of light. The "walls" of this "corridor" were the high-gloss, white enameled panel on one side and the fluorescent tube panel on the other. The light intensity on the growth chamber surface obtained by this arrangement was estimated at two thousand foot candles.

Prior to use, the entire algal growth unit was acid-washed, thoroughly rinsed, and steam sterilized at 20 lb per sq in. gauge pressure. The unit was then transferred over to sterile air without loss of positive pressure. Approximately 68 liters of suitable sterile aqueous media from the media preparation tank was then blown in. The media was cooled to the desired operating temperature and inoculated with the sterile cell suspension previously described.

The run was allowed to go as long as desired. When operated on a batch basis, growth was usually substantially complete in 9 to 13 days. Cell concentrations at the termination of these runs varied from 3.5 to 13.0 gm per liter with the maximum coming on a 12 day run. In comparison normal industrial mold fermentations show cell concentrations in the range of 25-50 gm per liter dry weight after 3 - 5 days. The system was also arranged so it could be operated on a semi-continuous basis; that is, a portion of the media sterilely removed for harvesting and this replaced with new sterile media. Under these conditions of harvesting and replenishing several times within every 24 hour period, the system was once kept operating for 31 days. During the course of any run, readings were made several times daily on the carbon dioxide and oxygen content of the entering gas, carbon dioxide and oxygen content of the vent gas, aeration rate both entering and leaving, media temperature at several points, coolant inlet and outlet temperatures, coolant flow rate, media flow rate in the illuminated growth chamber, pressure in the system, and several other readings merely instituted as a check on the general physical condition of the system itself. In addition, a small sample was removed once or twice daily. This sample was used to determine pH and cell concentration by means of actual cell counts and by determination of packed cell volume when centrifuged under specified conditions. The sample was also checked for presence of foreign organisms by means of microscopic examination and by culturing at 37°C in nutrient broth and on beef lactose agar.

When the run was complete, the unit was shut down and the media and suspended cells withdrawn. The cells were removed by means of a solid bowl supercentrifuge, air-driven at 54,000 rpm. Cell recovery was extremely good under these conditions. The cells were then freeze-dried.

The unit was easy to operate and control. Trouble-free performance, as far as the equipment was concerned, was obtained for more than a year of practically continuous operation.

Results of some typical runs are given in Table I. These growth rates closely parallel others in the literature.

DISCUSSION

Although the growth rates obtained in these particular experiments appeared satisfactory in comparison with those obtained by other workers in the field, it is obvious that the "theoretical maximum" still remains to be obtained. Moreover, it is by no means certain that the mass culture of algae would be economically feasible even if major advances were to be made in improving the growth rates, at least so long as no radical changes are forthcoming in the design and/or cost of the culture equipment. Therefore, it seems appropriate to examine in some detail the major factors affecting these growth rates and the cost of the resulting product in order to determine on a broad, general basis whether a solution to the present problems may be anticipated in the foreseeable future. In other words, there are certain limitations of which it is necessary to be fully aware in the attack on this problem. Some of these are discussed in the following sections.

A. Energy Considerations

Algae convert inorganic materials into organic compounds with the aid of light by means of a photosynthetic reaction. First consider the photosynthetic reaction itself

TABLE I

TYPICAL RESULTS IN THE ALGAL GROWTH PILOT PLANT

Algal Species	Type of Operation	Aeration Rate	CO_2 Content	Media Flow Rate	Operating Temperature	Operating pH	Length of Run	Media Volume	Final Cell Count	Final Cell Conc.	Total Algal Harvest: Fresh	Total Algal Harvest: Dry	Average Growth Rate, Area basis		Average Growth Rate, Volume basis	
		cu ft per min	per cent	ft per sec	°C		days	liters	Cells per cu mm	gm per liter	gm	gm	gm per sq meter per day	lb per sq ft per day	gm per liter per day	lb per gal per day
Chlorella pyrenoidosa	Batch	0.1	5.	0.82	24°	7-9	11.	83.3	940,000	6.55	2,823	545	8.5	0.0017	0.595	0.00496
Chlorella pyrenoidosa	Batch	0.1	5.	1.43	25°	6-8	12.	71.5	2,120,000	12.63	3,308	904	12.95	0.00265	1.05	0.00875
Chlorella pyrenoidosa	Batch	0.1	4.	0.41	25°	6-7.5	13.	67.6	1,390,000	9.52	2,237	644	8.52	0.00174	0.733	0.00611
Chlorella pyrenoidosa	Batch	0.3	5.	4.1	25°	6-7.5	11.	60.6	1,400,000	15.22	3,189	923	14.4	0.00295	1.39	0.0115
Chlorella vulgaris	Batch	0.2	5.	4.1	25°	6-7.5	13.	65.1	65,000	5.64	1,420	367	4.87	0.0010	0.433	0.00362
Chlorella vulgaris	Batch	0.2	5.	4.1	25°	6-7	13.	64.1	32,000	4.32	882	277	3.58	0.00073	0.323	0.00270
Scenedesmus obliquus	Batch	0.2	5.	4.1	29°	6-7.5	12.	70.7	380,000	9.20	1,702	650	9.32	0.00191	0.766	0.00639
Scenedesmus obliquus	Batch	0.25	5.	4.1	29°	6-7	12.	68.6	172,000	8.59	1,484	590	8.46	0.00174	0.716	0.00597
Chlorella pyrenoidosa	Semi-continuous	0.15	5.	4.1	28°-30°	6-7	31.7	74.5*	370,000	1.82	N.D.**	2,205	11.97	0.00245	0.063	0.000525

* Total volume harvested during run = 1,108

**N.D. = not determined.

without regard for the agent which is used to bring about this reaction. By means of photosynthesis, carbon dioxide and water are combined into an organic substance by means of a series of steps which are not completely understood. However, energy is required to make this reaction proceed. In nature this energy is received from sunlight. Although both carbon dioxide and water are transparent to sunlight, the green chlorophyll found in most living plants absorbs very completely most of the visible sunlight, extending from 4,000 A in the blue region to 6,500 in the red.[9] It then transfers this energy of sunlight to the water and releases hydrogen, which in turn reacts with carbon dioxide or with its reduction products and produces a variety of complex intermediate compounds, including sugars and other carbohydrates, represented by the formula $(CH_2O)n$, where n is an integral number. This process may be represented as follows:

$$H_2O + CO_2 + >112 \text{ kilocalories light} \xrightarrow{\textit{chlorophyll}} 1/n(CH_2O)\,n + O_2$$

Several interesting facts may be derived from a study of this reaction. Of primary importance is the energy required to make this reaction go. If a carbohydrate is burned with oxygen, 112 kilocalories are evolved by the organic material corresponding to one gm atom (12 gm) of carbon. Approximately the same energy is evolved on burning an equivalent amount of protein, and about twice this energy is evolved in the case of burning an equivalent amount of fat. To reverse this process would require at least 112 kilocalories per gm mol of carbon, (12 gm) if carbohydrate or protein is the product formed or twice this value in the case of a fat.

Since most algae are greater than 50 per cent carbon on a dry basis, it becomes possible to calculate the *absolute minimum energy requirement* per pound of dry product.

$$\frac{454 \text{ gm dry algae}}{\text{lb dry algae}} \times \frac{50 \text{ gm carbon}}{100 \text{ gm dry algae}} \times \frac{\text{gm-atom carbon}}{12 \text{ gm carbon}} \times \frac{112 \text{ kilocalories}}{\text{gm-atom carbon}} = \frac{2{,}120 \text{ kilocalories}}{\text{lb dry algae}}$$

Or in units which may be more easily visualized, this energy requirement is 2.46 kwh per lb dry algae. This is the absolute minimum energy requirement which must be absorbed by the chlorophyll and transmitted to the ingredients.

At a symposium on photosynthesis held in Chicago in 1947 under the auspices of the American Association for the Advancement of Science,[9] it was generally agreed that the maximum efficiency in photosynthesis is about 25 per cent of the absorbed energy stored as oxidizable organic material. This value was obtained independently with algae at the University of Chicago, at the Carnegie Institute of Washington, at Stanford, and at the University of Wisconsin. More recently Warburg, Burk, and associates[2] have reported a 70 per cent efficiency, but this value is under attack from various sources and the 25 per cent value is apparently the one generally accepted. Using this latter efficiency, the following *actual minimum energy requirement* may be calculated:

$$\frac{2.46 \text{ kwh}}{\text{lb dry algae}} \bigg| \frac{}{0.25} = 9.84 \frac{\text{kwh}}{\text{lb dry algae}}$$

$$\text{or } 8{,}480 \frac{\text{kilocalories}}{\text{lb dry algae}}$$

$$\text{or } 33{,}600 \frac{\text{Btu}}{\text{lb dry algae}}$$

When it is considered that this energy must be supplied as light in order for the photosynthetic reaction to proceed and that the conversion of electrical energy to light energy is only about 10 per cent efficient as a maximum, then it becomes obvious that sunlight must be depended upon as an energy source. Artificial light is economically impractical since a minimum of 100 kwh of electrical energy would be consumed to produce sufficient light for the formation of one pound of dry algae. With electrical energy at 7 mills per kwh, the cost of electricity alone would be at least 70 cents per pound of dry algae, if electric lights were used as the energy source. Thus, it may be seen that sunlight is probably the only practical energy source for the mass culture of algae.

M. Telkes[28] reports the amount of solar energy received at the earth's surface at several locations to be as shown in Table II.

Half of this incident light energy is absorbable by chlorophyll. The remainder of the solar energy incident at the earth's surface lies in the infra-red region and is not absorbable by chlorophyll or utilizable in photosynthesis. Therefore, if an average value for the incident solar energy of 500 kilocalories per sq ft per day is assumed, then the amount of this energy which can be absorbed by chlorophyll is half this, or 250 kilocalories per sq ft per day.

Knowing this value of energy supplied by the sunlight and already having seen that 8,480 kilocalories of absorbable energy are necessary for the formation of one pound of dry algae, it is possible to calculate the *absolute maximum possible growth rate* for an algae depending upon the sun as a source of energy.

$$\frac{250 \text{ kilocalories}}{\text{sq ft - day}} \bigg| \frac{\text{lb dry algae}}{8{,}480 \text{ kilocalories}} = 0.0295 \frac{\text{lb dry algae}}{\text{sq ft - day}}$$

TABLE II

Location	North Latitude	Amount of Solar Energy Received Per Day					
		June		December		Yearly Average	
		kilocalories / sq ft-day	Btu / sq ft-day	kilocalories / sq ft-day	Btu / sq ft-day	kilocalories / sq ft-day	Btu / sq ft-day
San Juan, Puerto Rico	18°	504	2,000	388	1,540	488	1,940
Honolulu, Hawaii	21°	605	2,400	366	1,450	479	1,900
Miami, Florida	25°	555	2,200	278	1,100	378	1,500
La Jolla, California	33°	479	1,900	252	1,000	388	1,540
Fresno, California	36°	706	2,800	141	560	434	1,720

This rate of growth of algae represents a yield of 25 per cent for the conversion of absorbed light energy into organic materials, or a yield of 12½ per cent for the conversion of incident light energy into organic materials. Such a yield is apparently the absolute maximum and could only be obtained if all other factors affecting the growth rate were held at their optimum. There is, in fact, some doubt if this yield could be obtained in sunlight, which has already been shown to be the only practical energy source for this process. A serious limitation on the yield per unit amount of light absorbed in the outdoor growth of algae, even with all other factors at their optimum, is the high intensity of sunlight during a large part of the day. Algae cells actually reach their maximum capacity for photosynthesis when illuminated with light of average intensity 10 per cent of that of full sunlight.[13 16 17] In none of the experiments in which algae have been exposed to natural sunlight has the yield of conversion exceeded 2½ per cent. An energy yield of 2½ per cent would result in a growth rate of approximately 0.006 lb dry algae per sq ft per day.

B. Turbulence Considerations

The total amount of organic material which can be produced from sunlight by growing plants increases with the intensity of light up to a certain point (saturation intensity), but beyond that point the amount produced does not increase, and the amount produced per unit of light decreases rapidly when the intensity of light increases. Light of high intensity apparently stimulates a process of photo-oxidation which partially offsets some of the photosynthesis.[24]

It might be of interest here to quote Bessel Kok on this phenomenon:

"Photosynthesis, the basic process of light transformation underlying algae growth, does not run faster and faster as more light is given, but finally reaches a certain speed, limited by internal cellular factors, typical for each strain of plant material and influenced by the prevailing temperature. Photosynthesis is known to be a chain process, a photochemical reaction being followed (or preceded) by several non-photochemical steps, probably of enzymatic character. It is one of these so called "dark reactions" which at a certain overall rate will reach its maximum speed and in this way will impose a ceiling, the saturation rate, on the maximum rate of the whole chain.

"We can consider the limiting steps of this chain as a reaction in which definite numbers of enzyme molecules are at work transforming intermediate products from one form to another. At maximum speed, nearly all enzyme molecules will be loaded and go through their cycle in a certain time. Only when such a molecule becomes free again can it be reloaded by a preceding, photochemically formed intermediate.

"When much more light is absorbed by the cells than can be handled in this reaction, only a fraction of the light will actually be used and its energy fixed in organic material. But if this same high intensity were given in short flashes, each flash short enough not to over-shoot the amount of available enzyme molecules, and a dark period were interposed which was long enough to allow these molecules to discharge completely, no light would be wasted."[13] (That is, the 12½ per cent maximum energy conversion would be realized.) Kok continues on this same subject as follows:

"Of course, nothing would be gained in practice by periodically intercepting the sunlight by some mechanical device; the light losses instead of occurring within the cells, would occur outside. This difficulty might be avoided by use of very dense cultures of algae stirred so that the cells would alternately shade one another, thereby exposing themselves to alternate light and dark periods. The population density and turbulence of the culture could be adjusted so as to provide the ratio of light and dark periods necessary to effect maximum photosynthesis by the individual cell.

"The mere 'spreading out' in time of bright light over more cells so that each gets on the average no more light than it can handle is, however, not sufficient of itself to insure maximum photosynthetic efficiency. The timing schedule must also fit the cell's requirements. Only in case the light - dark cycles are shorter than a given time (determined by the limiting steps described above) can substantial increase in yields be expected."[13]

Kok investigated the light-dark cycle for *Chlorella pyrenoidosa*[13] and found maximum efficiency to result when the cells were illuminated for 0.002 seconds and darkened for 0.020 seconds. The optimum yield was halved under circumstances whereby the cells were illuminated for 0.010 seconds and darkened for 0.100 seconds. Jack Myers[21] investigated this same factor and found no increase in growth rate when light of high intensity was given in intermittent flashes over that rate obtained when an equivalent amount of energy was supplied continuously at lower intensity; thus indicating again that low intensity light is to be desired from the point of view of maximum conversion of incident energy to organic material.

The maximum growth rate of algae actually obtained and reported in the literature was through the application of Kok's intermittent-light theory in a small scale laboratory apparatus. The investigator was Edwin A. Davis[10] of the Carnegie Institution of Washington and he describes his apparatus as follows:

"A special apparatus was constructed which permitted cells to be cultured in a thin layer (6.4 mm or approximately ¼ in.) exposed to bright light, approximately equivalent to sunlight, and subjected to various degrees of turbulence. Culture turbulence was accomplished by means of a spinning stainless steel rotor suspended in the culture, forming its inner boundary. By spinning the rotor at different speeds various degrees of turbulence were achieved. Carbon dioxide in air was introduced through the bottom of the chamber, and bubbled up through the culture.

"The influence of turbulence on growth was determined at the very high culture density of about 150 gm per liter fresh weight. (Note: This concentration was prepared

artificially and is approximately equivalent to 30 gm per liter or 0.25 lb per gal dry weight.) The cells were transferred to fresh medium every 12 hours in order to provide ample nutrients and to remove any inhibitory excretory products that might be produced. The light was provided by six 300-watt reflector spot lamps equally spaced in a circle with their front surface 20 cm from the culture. Approximately 7,000 foot candles was thus provided at the culture surface, and nearly all the light was absorbed in a one-mm layer of the suspension."

The growth rates which Davis obtained with *Chlorella pyrenoidosa* are as follows:

Rotor speed (rpm)	Growth rate (lb/sq ft/day)
0	0.00516
16	0.00700
208	0.00880
475	0.00885

As stated before, this rate of 0.00885 lb per sq ft per day is by far the best which has yet been found in the literature. Davis attributes these "good" rates to the design of the apparatus, the turbulence, the close temperature control which he maintained, and the frequent provision of fresh medium.

These rates may be compared with the maximum rate reported by Jack Myers,[20] one of the oustanding experimenters in this field, in an annular chamber apparatus under continuous illumination and without mechanical agitation. He reports 0.00061 lb per sq ft per day. Davis[10] in his apparatus and under his conditions increased this value more than ten fold, but under his highly specialized conditions he attained only 30 per cent of the absolute maximum rate of 0.0295 lb per sq ft per day which has been shown to be the ultimate if the solar energy supply were the only limiting condition. Therefore, the general conclusion is that fundamentally the possibility exists of raising the efficiency of utilization of sunlight by subjecting algal cells to the proper regime of intermittence of illumination, but (to again quote Bessel Kok) "that the maximum realization of this objective in large-scale developments through increased turbulence of algal cultures would be difficult technically and unsound economically."[13]

However, agitation of some sort would probably be an essential requirement since it serves two other very useful purposes; namely, keeping the cells in suspension and maintaining equilibrium conditions between the necessary nutrients and each cell. Thus it can be seen that extremely highly specialized conditions and equipment are necessary for obtaining satisfactory growth rates of algae. Unless these special conditions are met exactly, the yield from algal crops would exceed only slightly, if at all, that obtainable from our better land crops. Farrington Daniels[9] estimates that an acre of open lake would produce about two tons per year (0.00025 lb per sq ft per day) of dry organic material in the form of algae. This is roughtly equivalent to the yield of organic matter which may be obtained from grass, corn stalks, weeds, and some forests.

This desired agitation could probably best be supplied by circulating the media at a rate sufficient to: (a) prevent substantial settling out of the algal cells, and (b) give a Reynolds number sufficiently high to place the flow pattern in the turbulent range, and also to give a turbulence with the best regime as regards light and dark intervals for the suspended algal cells.

The optimum flow rate would depend upon the physical design of the particular equipment. However, some information is known concerning actual flow rates in experimental equipment. The Arthur D. Little pilot plant[6] reported that a flow rate of 0.3 ft/sec in a 4 ft wide tube with a 2.5 in. depth of culture (equivalent to 110 gal/min) was insufficient to keep the algal cells in suspension. At velocities of 1 to 1.5 ft/sec, in a 15 in. wide channel, they report that no settling occurred. Mituya, *et al*,[7] report that at flow rates of 1 ft/sec in their apparatus (a 3 ft wide trough), the algal cells tended to settle out. In our own experiments in one in. diameter glass pipe, some tendency of the algal cells to settle out at flow rates as high as 4 ft/sec was noted. However, these runs were of two to three weeks duration at high cell concentration in a batch system. The settling effect might have been much less pronounced in a continuous system at lower cell concentrations.

Based on the limited data available it would appear that a flow rate of at least 1 - 1½ ft/sec would have to be maintained in order to keep the cells reasonably well suspended. The power expended (in terms of cost per pound of algae) to maintain this flow rate would depend upon the cell concentration and the design of the equipment. Therefore, it is difficult to estimate.

The Arthur D. Little experimenters[6] reported their friction loss as about 4 in. of water per 500 ft of run at a flow rate of 1¼ ft/sec in a 4 ft wide tube with a 2.5 in. depth of culture. Using this as a basis, and assuming the absolute maximum growth rate of 0.0295 lb/sq ft/day a rough estimate of power consumption for circulation may be made:

$$\frac{24\text{ hr}}{\text{day}} \times \frac{3600\text{ sec}}{\text{hr}} \times \frac{}{500\text{ ft}} \times \frac{1.25\text{ ft}}{\text{sec}} \times \frac{1\text{ gal}}{1\text{ gal}} \times \frac{8.33\text{ lb}}{\text{gal}} \times 4\text{ in} \times \frac{\text{ft}}{12\text{ in}} \times \frac{\text{kwh}}{2.655\text{x}10^2\text{ft-lb}} = \frac{0.0226\text{ kwh}}{\text{day - gal}}$$

At a pump efficiency of 80 per cent this power requirement becomes 0.028 kwh per day per hour.

The total volume in this assumed system would be

$$(500\text{ ft})\ (4\text{ ft})\ (\frac{2.5}{12}\text{ ft})\ (7.48\text{ gal/cu ft}) = 3{,}120\text{ gal}$$

The absolute maximum yield of algae which could be obtained from this assumed system would be 0.0295 lb per sq ft per day. (500 ft) (4 ft) = 59 lb per day.

Therefore, the *minimum* power consumption for circulation of media would be

$$\frac{0.028\text{ kwh}}{\text{day - gal}} \times 3{,}120\text{ gal} \times \frac{\text{day}}{59\text{ lb}} = \frac{1.48\text{ kwh}}{\text{lb algae}}$$

With 7 mills per kwh power, this gives a minimum cost of one cent per lb. In their actual experiment the

growth rates never exceeded 9 per cent of the maximum, so the actual cost of circulation must have been in the neighborhood of 11 cents per lb of algae produced.

C. Carbon Dioxide Considerations

Another factor which could limit the growth rate of algae is the carbon dioxide supply. Farrington Daniels[9] has estimated that algae growing free in an open pond and depending on the normal atmosphere (0.03 per cent carbon dioxide) for its carbon dioxide will produce only at the rate of approximately 2 tons per year per acre (0.00025 lb per sq ft per day). Many factors enter into this low growth rate under natural conditions, but one of primary importance seems to be the low carbon dioxide concentration in the atmosphere. For maximum growth rates, it has been determined that the culture medium must be saturated with carbon dioxide at all times. It is universally agreed by all investigators that aeration with a mixture of 5 per cent CO_2 in air is probably about the best condition. Spoehr and Milner[26] found that the rate of growth of algal cultures aerated with plain air was only one-tenth that of cultures aerated with 5 per cent CO_2 in air. Edwin A. Davis,[10] however, found that algae aerated with plain air could be grown at a rate equal to 82 per cent of that obtained when using 5 per cent CO_2 in air, provided that a sufficient amount of the plain air were blown through the culture medium to maintain the medium saturated with carbon dioxide at all times.

Since carbon dioxide is the source of the carbon in the algae cells, and since it is known that algal cells usually assay greater than 50 per cent carbon on a dry basis, it is possible to calculate the minimum CO_2 requirement for growing algae by means of a carbon balance.

$$\frac{0.50 \text{ lb carbon}}{\text{lb. dry algae}} \left| \frac{\text{lb-mol carbon}}{12 \text{ lb carbon}} \right| \frac{1 \text{ lb-mol } CO_2}{\text{lb-mol carbon}} \left| \frac{44 \text{ lb } CO_2}{\text{lb-mol } CO_2} \right. = 1.83 \frac{\text{lb. } CO_2}{\text{lb dry algae}}$$

The above assumes a 100 per cent yield on the carbon supplied to the culture. Actual obtained yields by different investigators, J. Myers[19] and M. J. Geoghegan,[11] have been 95 per cent and 83 per cent, respectively, when the carbon was supplied as 5 per cent CO_2 in air.

With carbon dioxide gas selling at 3.5 cents per pound in its cheapest form (as dry ice), the cost of carbon dioxide would be at over six cents per lb of dry algae. It is somewhat improbable that this process can be run economically if purchased CO_2 is used as a carbon source.

Several alternate carbon sources are available. First, the method of Davis [10] could be used whereby plain air (which contains about 0.03 per cent CO_2) is bubbled through the culture medium at a rate sufficient to keep the medium saturated with carbon dioxide at all times. It is doubtful if under these conditions a high carbon yield could be obtained, but this is not known for sure as he gives no data on this point. It is known that there will be a decrease in algae growth rate over that obtainable with 5 per cent carbon dioxide in air. However, assuming a 100 per cent carbon yield, the amount of air which must be passed through the media may be calculated:

$$\frac{1.83 \text{ lb } CO_2}{\text{lb dry algae}} \left| \frac{\text{lb-mol } CO_2}{44 \text{ lb } CO_2} \right| \frac{359 \text{ cu ft } CO_2}{\text{lb-mol } CO_2} \times$$

$$\times \frac{1 \text{ cu ft air}}{0.0003 \text{ cu ft } CO_2} \left| \frac{28 \text{ lb air}}{359 \text{ cu ft air}} \right. = 3{,}900 \frac{\text{lb air}}{\text{lb dry algae}}$$

$$\text{or } 50{,}000 \frac{\text{cu ft air at S T P}}{\text{lb dry algae}}$$

The cost of this air would depend upon the degree of compression necessary, which in turn would depend upon the design of the algae culture equipment used. Since the gas distribution system would have to be quite elaborate in an algae growth unit it seems reasonable to assume that these gases would have to be compressed at least to the range of 20 - 40 psig prior to use. For isothermal compression the power requirement for this operation may be calculated:

$$W = \int PdV = RT \ln \frac{V_1}{V_2} = RT \ln \frac{P_2}{P_1}$$

$$= 2.3\, RT \log \frac{P_2}{P_1} = \frac{2.3}{} \left| \frac{1546 \text{ ft-lb}}{{}^\circ\text{R -lb-mol}} \right| \frac{530^\circ\text{R}}{} \times$$

$$\times \frac{\text{lb-mol}}{28 \text{ lb}} \left| \frac{\text{kwh}}{2.655 \times 10^6 \text{ft-lb}} \right| \frac{\log (45)}{15}$$

$$= 0.012 \text{ kwh/lb of air.}$$

At a compressor efficiency of 80 per cent and a power cost of 7 mills per kwh, this gives a power cost of compression of 0.01 cents per lb of air. Since it has been shown that a minimum of 3900 lb air per lb dry algae would be required, this method would give a cost of 39 cents per lb of algae for the CO_2. Thus this method may be disregarded even with the cheapest known power.

Another possible source of carbon dioxide would be boiler stack gas. This gas usually runs 14 - 16 per cent carbon dioxide. The main drawbacks to the use of this material are as follows:

(1) These gases usually contain some fly-ash and from 0.1 - 0.5 per cent sulfur dioxide. The effect of these on the growth rate of algae is not known and would have to be determined. It is probable that these gases might have to be scrubbed prior to use in order to remove these ingredients.

(2) The stack gases would have to be pre-cooled before being passed into the media since the algae are heat sensitive.

(3) The stack gases would have to be compressed to a suitable working and distribution pressure prior to use, and the resulting heat of compression removed.

(4) The stack gases would have to be diluted to a carbon dioxide concentration of 5 per cent. At the 14 - 16 per cent carbon dioxide concentration the carbon yield would probably be quite low since it has been shown experimentally that no advantage accrues when the carbon dioxide content of the aerating gas exceeds 5 per cent.[26]

(5) Carbon dioxide in the form of a by-product from boiler stack gases is available 24 hours per day, but can

be utilized by the algae only during the day-light hours. Therefore, unless an expensive method of collecting and storing it were installed, useful CO_2 could probably only be obtained 10 - 12 hours per day.

If these stack gases are diluted with air to a 5 per cent carbon dioxide concentration and then compressed to the 20 - 40 psig range, the cost of the carbon dioxide by this method would be as follows: (assuming stack gases are obtained *free* as a by-product)

$$\frac{1 \text{ lb-mol } CO_2}{44 \text{ lb } CO_2} \left| \frac{359 \text{ cu ft } CO_2}{\text{lb-mol } CO_2} \right| \frac{1 \text{ cu ft diluted gas}}{0.05 \text{ cu ft } CO_2} \times$$

$$\times \frac{28 \text{ lb diluted gas}}{359 \text{ cu ft diluted gas}} = 12.75 \frac{\text{lb diluted gas}}{\text{lb } CO_2}$$

Since the power consumption for compression would be approximately 0.015 kwh per lb of diluted gas, the power consumption per lb CO_2 would be (12.75) (0.015) = 0.19 kwh. At a power cost of 7 mills per kwh, this results in a compression cost of 0.14 cents per lb of carbon dioxide. This figure includes power cost for compression only. Actual cost would probably be in the range of one cent per lb of CO_2. It may be seen that the use of stack gases or some other carbon-dioxide-rich waste gas seems to be most advantageous from an economic viewpoint, compared to the four cent per lb dry ice.

It might be of some interest to estimate the size of the power plant necessary if the waste-gas from this power plant were to be used as a carbon dioxide source for an algae growth unit. Since in a power plant using high carbon content fuel one kwh is generated for approximately every 1 lb of carbon burned, the size of such a plant may be estimated.

$$\frac{1 \text{ lb } CO_2}{1 \text{ lb } CO_2} \left| \frac{12 \text{ lb C}}{44 \text{ lb } CO_2} \right| \frac{1 \text{ kwh}}{1 \text{ lb C}} = 0.272 \frac{\text{kwh}}{\text{lb } CO_2}$$

D. Consideration of Other Sources

One other possibility exists as a carbon source for algal growth. Carbon might be supplied as the bicarbonate. Some investigators have used this technique and growth rates were much lower than when carbon dioxide was used as the carbon source. However, it is believed that the use of bicarbonate may not have been completely investigated and therefore this remains a possibility. The amount of bicarbonate needed can be easily calculated by a carbon balance if a 100 per cent carbon yield is assumed.

	Lb. required per lb of dry algae	Price per lb. of the carbon source* ($)	Cost per lb of dry algae ($)
Sodium bicarbonate	3.5	0.03	0.11
Potassium bicarbonate	4.2	0.24	1.00

*Prices per pound of these compounds are approximate only.

It can be seen from the above that bicarbonates are not a cheap carbon source for algae culture. Therefore, this possibility can be ruled out as uneconomical.

E. Nitrogen Considerations

A fixed nitrogen source is another primary requirement for the growth of algae. Algal cells usually contain about 7-11 per cent nitrogen on a dry basis, corresponding to a protein content of 45-65 per cent. The nitrate and ammonium ions are the sources of fixed nitrogen used by almost all investigators in their experimental work with algal cultures, although some organic sources have been investigated and urea and glycine found satisfactory. It is understood that some investigation is now under way on the possibility of using amino nitrogen, but the results are not known.

Assuming a nitrogen content of 8 per cent (corresponding to 50 per cent protein), and a 100 per cent nitrogen yield (J. Myers[19] has shown that a 95 per cent nitrogen yield can be obtained), then it is possible to calculate the nitrogen requirement for algae growth in terms of some of the possible nitrogen source compounds.

	Lbs required per lb of dry algae	Price per lb of the nitrogen source ($)*	Cost per lb of dry algae ($)
Potassium nitrate	0.58	0.09	0.047
Ammonium nitrate	0.23	0.019	0.004
Ammonia	0.10	0.042	0.004
Urea	0.17	0.025	0.004
Glycine	0.43	1.40	0.600

*Prices per pound of these compounds are approximate only

On the basis of the above it would seem that ammonia or ammonium nitrate would be the preferred nitrogen source. Davis and Dedrick report,[4] however, that best growth rates may be obtained with urea as the nitrogen source.

F. Consideration of Other Major Nutrient Requirements

In addition to the requirement for carbon dioxide and fixed nitrogen, algae also require magnesium, phosphorus, and potassium for normal growth and photosynthesis. There is also evidence that a sulfur deficiency will affect the chlorophyll formation (and thus photosynthesis) in algae.

Some results of analyses of dry algal (*Chlorella pyrenoidosa*) cells are as follows:

	By R. W. Krauss[3]	By M. J. Geoghegan[5]
Magnesium	0.26 - 1.51%	0.5%
Sulfur	0.91	1.1
Potassium	0.04 - 1.44	1.5
Phosphorus	0.94 - 1.51	1.1

Magnesium and sulfur are usually supplied as $MgSO_4 \cdot 7 H_2O$. Assuming 100 per cent yield on these elements and using the analysis of Geoghegan,[5] it is found that 0.085 lb of $MgSO^4 \cdot 7 H^2O$ is required per lb of dry algae.

Potassium and phosphorus are usually supplied to the media as $K H_2PO_4$. Under the same assumptions it may be determined that 0.052 lb of $K H_2PO_4$ is required per lb of dry algae.

The cost of these four major nutrients would amount to at least 1.3 cents per lb of algae (based on $MgSO_4 \cdot 7 H_2O$ at 3.55 cents per lb and $K H_2PO_4$ at 18.85 cents per lb.)

G. Micro-Nutrient Considerations

Another factor which is known to be able to limit the growth of algae is the supply and concentration of the various trace elements needed by the growing cells. A large amount of work has been done on determining the

trace element requirements, but as yet really not too much is known about this problem, and it is still a subject for further investigation. The main problem lies in the fact that a number of these trace elements are needed for growth, but the range between the required amount and the toxic amount is extremely narrow. As stated by J. Myers, "It is a serious problem to provide adequate amounts of the various micro-elements, and to maintain their availability without exceeding the limits of toxicity."[20]

Iron and **manganese** appear to be universal requirements of algae. Both apparently enter into the photosynthetic chain reaction in some manner. Some problems have been encountered by investigators in maintaining a ferric ion concentration in the media at the operating pH high enough so that this factor does not become limiting. Therefore, ethylene diamine tetra-acetic acid (Versene) is generally incorporated in the media as a chelating agent.

The other more common constituents of algal media have been summarized by J. Myers as follows:

"**Zinc** has been demonstrated to be a growth requirement for a number of flagellates and for *Chlorella.* Algae do not require **calcium** at as high a level as do the higher plants, but a calcium requirement of 5 ppm in the media has been established for *Chlorella.* A **molybdenum** requirement has been demonstrated for a number of single-cell organisms, but it is not definitely known whether molybdenum is required by algae. However, it is generally included in the media. **Copper** and **boron** are also generally included in algae culture media, although a definite requirement for these materials has not yet been proved or disproved. Copper has been shown to be toxic for photosynthesis in *Chlorella* at concentrations exceeding 1 x 10^{-7} molar."[18]

Some other trace elements which often are included in the media, but for which no definite requirement has been established are as follows:

vanadium	nickel	wolfram
chromium	cobalt	titanium

No attempt is here made to arrive at a cost for these trace elements. Under optimum conditions such as are being discussed throughout this report, their cost should not exceed 0.2 cents per lb. In reality, however, this cost might be orders of magnitude higher than this.

H. Consideration of the Absolute Maximum Rate of Photosynthesis

In an earlier section of this report it was shown that sunlight was the only practical energy source for the cultivation of algae. Moreover, it was pointed out that this fact imposes a "ceiling" on the growth rate of algae. This "ceiling" was based on energy considerations alone and was determined to be 0.0295 lb per sq ft per day.

However, Rabinowitch[24] (and others) have pointed out that a simultaneous increase of carbon dioxide supply and light supply leads to saturation of photosynthesis long before the carbon dioxide considerations or energy considerations become limiting. This is attributed to certain intrinsic internal factors (such as limited availabilty of certain catalysts) which impose an "absolute" ceiling (i.e., a ceiling independent of both carbon dioxide supply and light intensity) on the maximum rate of photosynthesis. This maximum rate of photosynthesis is not a function of the efficiency of light but is a measure of the amount of limiting enzyme present in cells. The maximum rate of photosynthesis is a constant of the plant. The only external factor that affects it (apart from the presence of poisons or inhibitors) is temperature.

Considerable effort has been expended by various investigators in determining the value of this maximum rate of photosynthesis for various plants. Rabinowitch[24] has collected a number of these values and for algae it is about 15 gm CO_2 per hr per 100 gm algae, corresponding to a maximum production rate of 5.5 gm algae per gm algae per day.

This figure leads us into an interesting comparison of of the maximum reproductive rate of algae as compared to some other microorganisms. The table below lists for several types of organisms the number of cells resulting in 24 hours from the normal reproduction of *one* cell and its descendants.

Number of Cells in 24 Hours Resulting From Normal Reproduction of Original Cell and its Descendants (approx)

Type organism	
Alga *(Chlorella pyrenoidosa)*	7
Protozoa *(Tetrahymenageleii)*	55
Yeast *(Willia anomala)*	1 x 10^6
Bacteria *(Escherichia coli)*	1 x 10^{26}

(The above calculated from growth constants listed by J. Myers.)[18]

Thus, it may be seen that algae are essentially slow growers as compared to other types of microorganisms. Therefore, it is important when thinking of algae that we do *not* make the mistake of comparing yields of cellular material obtained in algae cultivation with yields of cellular material obtained in our common microbiological fermentation processes. Although it is true that under specialized conditions algae growth rates are higher than those of the usual land plants, these growth rates still do not compare with those of the common cultivated microorganisms.

For instance in many mold fermentations there is a rate of cell formation amounting to 30 gm per liter of media in approximately 100 hours. Algae units are run in the neighborhood of 0.1 - 1.0 gm per liter and only in batch units run for several weeks does the algae concentration approach 10 gm per liter.

I. Temperature Considerations

Another factor which must be considered in the mass culture of algae is the temperature at which the algae are grown. Algae are extremely temperature sensitive and exhibit a very narrow range within which maximum growth is obtained. In the case of ordinary strains of *Chlorella* this optimum is 25°C.

This temperature sensitivity represents a serious problem, especially since it has already been shown that the sun is the only practical energy source for the photosynthetic reaction. In the discussion earlier on energy, it was shown that even at maximum efficiency the algae would utilize only 12½ per cent of the solar energy inci-

dent upon it. All of the energy which is incident upon the algae culture and which is not used in the photosynthetic reaction will evince itself in the form of heat.[14] Therefore, seven units of heat energy must be dissipated for every one unit of energy actually utilized, if a constant temperature is to be maintained. The minimum amount of heat which must be dissipated can easily be calculated:

$$\frac{33{,}600 \text{ Btu utilized}}{\text{lb dry algae}} \left| \frac{7 \text{ Btu heat produced}}{1 \text{ Btu utilized}} \right. = 235{,}000 \, \frac{\text{Btu heat}}{\text{lb dry algae}}$$

To remove all this heat by standard commercial means would require the almost fantastic total of 0.8 standard commercial tons of refrigeration per lb of dry algae produced per day.

Of course, all the excess heat would not be removed by mechanical means. Some would be dissipated by radiation. Some would be lost through the evaporation of water from the culture media. However, if culturing were done in thin layers, water loss by evaporation would present a problem and this loss would have to be continuously replaced in order to maintain nutrient concentrations and total salinity at their optimum values. If culturing is not done in thin layers so that the water loss will have little effect, then more problems will be encountered in the subsequent recovery steps as a result of the lower population density of the algae and the resulting larger volumes of water which must be processed per unit of production.

If it is assumed that only 25 per cent of this heat need be removed by refrigeration, then the minimum power cost for this refrigeration may be calculated.

$$\frac{(0.25)\ (235{,}000) \text{ Btu removed}}{\text{lb dry algae}} \left| \frac{1 \text{ Btu expended}}{6 \text{ Btu removed}} \right| \frac{1 \text{ kwh}}{3415 \text{ Btu}}$$

$$= 2.87 \, \frac{\text{kwh}}{\text{lb dry algae}}$$

At 7 mills per kwh this results in a cost of 2 cents per lb of algae. This is power cost for refrigeration only, and does not include any power costs for circulating the cooling medium or any other charges which would of necessity be associated with this refrigeration and cooling system.

A strain of *Chlorella* has been isolated by Sorokin and Myers[25] which appears to have a temperature optimum at 39°C. If this strain proves suitable for mass culture, then it would somewhat simplify the refrigeration problem. At this higher temperature less refrigeration would be required since more heat would be dissipated by radiation. This strain would have a slight drawback in that there would be no hope of it operating at or near its maximum photosynthetic efficiency, until the media becomes warmed up to 39°C at the beginning of each day.

There is another possible need for refrigeration in the culturing of algae. Under the conditions prevailing in the outdoor culture of *Chlorella* depending upon the sun as an energy source, the algae can grow only during the daylight hours. During the hours of darkness it uses up a portion of the organic matter formed in the light. It has been shown[15] that this adverse effect on yield can be partially offset by cooling the culture to 15° at night, at which temperature respiration is reduced. An economic balance on any given system would be necessary to determine if the saving obtained through increased yields would be worth the cost of refrigeration.

J. Considerations of Sterility

Another problem in the mass culture of algae is the fact that our results and those of many other investigators show a closed, sterile system may be required and all culturing would have to be done under aseptic conditions. Cook[8] reports that there are strong indications that certain molds and bacteria will cause a considerable decrease in yields. On the other hand, it is known[23,27] that some algae will produce material with anti-bacterial activity through the photo-oxidation of certain unsaturated fatty acids (for example, chlorellin by *Chlorella*). Some investigators have cultured their algae with no attempt to maintain sterility, and report no substantial contamination. Therefore, this matter has not been definitely settled and is a subject for further investigation. A system not requiring sterile conditions would result in appreciable savings. The cost of sterilizing all media would by itself almost make the process uneconomical.

Whether or not a sterile operation is required is still a matter for further investigation. However, it is certain that a method of sterilizing the system must be provided. Otherwise, a protozoan infestation could cause the entire operation to cease for an indeterminate period.

K. Consideration of Growth Inhibiting Excretory Products

Still another hindrance to the maximum growth rate of algae is the growth inhibiting excretory products produced by the algae themselves. *Chlorella* have been shown[23,27] to produce a substance termed chlorellin which renders the cells incapable of reproducing themselves. This material would probably have to be removed if maximum growth rates and population densities are to be obtained. Also, it would have to be removed if there were to be any attempt to re-use the media water and any nutrients which may be left in this water. Davis[10] attribuated his improved growth rates partially to the fact that he transferred his cells to completely new media every 12 hours, thus eliminating growth inhibiting material.

Chlorellin is known to be heat unstable,[22] and could probably be broken down by heating the used media. Moreover, it may be absorbed on carbon.[23] However, such treatments would be another item of expense and an economic balance would be necessary to determine whether it is feasible to remove the chlorellin and recycle the water and unused nutrients, or whether it would be better to discard this material and replace it with fresh water and nutrients.

More investigation is required to determine if this factor is important.

L. Consideration of the "Theory of Optimum Catch"

Another possible limiting factor in the growth of algae

is a law of nature termed the "theory of optimum catch". This theory, as explained by Ketchum, Lillick, and Redfield, is as follows:

"In brief, the theory of the optimum catch states that every population has an optimum density for the production of new individuals. If the population is too dense, competition or other adverse factors limit the multiplication rate so that fewer surviving individuals are produced. In a small population, even though the multiplication rate may be large, only a small number of new individuals can be produced because of the small parent stock. It follows that the maximum harvest can be made at that level where the product of the multiplication rate times the size of the population is at a maximum."[12]

This phenomenon results to some extent from the growth characteristics of the population. Generally speaking, the growth of a population can be broken down into six distinct phases, as follows: [2]

(a) Lag phase — the growth rate is very slow and dependent upon the species and the conditions of the system, but is independent of the population density.

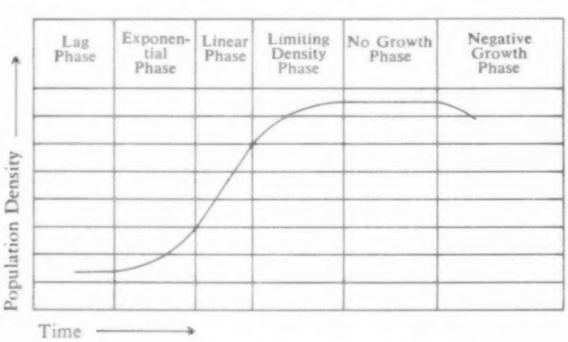
(b) Exponential phase — the growth rate is directly proportional to the population density and follows a logarithmic growth curve. The growth rate may be expressed $dc/dt = kc$.

(c) Linear phase — the growth rate is constant and is independent of the population density. The growth rate may be expressed as $dc/dt = K$.

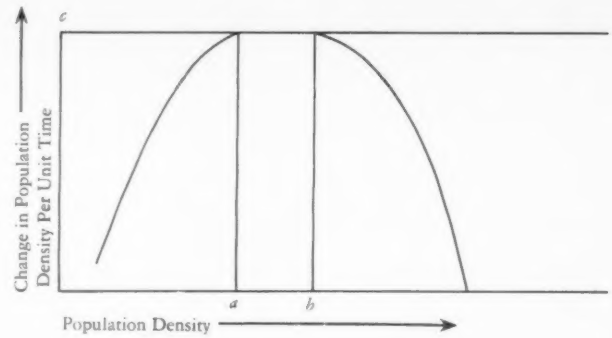
(d) The limiting density phase — the population continues to increase but at decreasing rate. The growth rate may be expressed as $dc/dt = M(A - Bc)$.

(e) No growth phase — the population remains constant and there is no growth. $dc/dt = O$.

(f) Negative growth phase — the population density actually decreases.



When the first derivative of the above typical growth curve is taken and the first derivative at any population density is plotted against that population density, another typical curve is obtained which explains graphically the theory of the optimum catch.



Thus, from the above, it can be seen that there is a certain population density range (a to b) at which the growth rate (c) is a maximum. This is the theory of the optimum catch.

Algae have been found to conform to the theory of the optimum catch.[12] This is of extreme importance since it determines the concentration at which algae can be grown, and therefore, the amount of liquid which must be handled in the recovery stages of the process.

Ketchum, Lillick, and Redfield,[12] found *Chlorella pyrenoidosa* to be the fastest grower of the algae investigated, and also the best when evaluated by the theory of the optimum catch. Their experimental results with *Chlorella* are as follows:

Population density at which maximum growth was obtained	0.0019-0.0050 lb/gal
Maximum growth rate	0.00062 lb/gal/day

Milner[14] found the optimum population density for *Chlorella* to be about 0.0040 lb per gal, which checks the above results. Cook,[8] in a continuous culture apparatus, found the optimum population density to be 0.0032 lb per gal. At this optimum density, he obtained a maximum growth rate of 0.0040 lb per gal per day. At these concentrations, about one ton of water would have to be processed for one pound of dry algae produced.

Assuming that the algae unit were operated at a concentration of 0.01 lb per gal, then 100 gal of water would have to be processed in order to obtain 1 lb of algae. In all experimental units, this processing has been done by centrifugation. However, it is conceivable that this operation might be conducted on a string discharge rotary filter. This would result in a cost of about 15 cents per lb of algae.

The cells as received from the centrifuge or filter would be 75 - 80 per cent water. This would have to be removed by drying, and 4 - 5 lb of water per lb of dry algae would have to be removed in the dryer. The accepted laboratory method of drying this material is by freeze-drying. There is some indication that the cells form a gummy cake if more conventional drying methods are used. This is another problem requiring further investigation.

It may be "guesstimated" however, that this would add another 5 cents to the cost of the algae.

After drying, the cells would probably require milling and packaging. It is estimated that this would cost one cent per lb of algae.

M. Summation of Cost Considerations

Assume:

(a) Growth rate of 0.01 lb per sq ft per day. This rate is one-third of the maximum, but about four times higher than any that has yet been actually obtained in any reasonable-sized equipment.

(b) Concentration of 0.01 lb per gal. This is two or three times higher than optimum as determined by theory of optimum catch.

(c) A plant that produces 100 tons of dry algae product per day.

(d) That carbon dioxide is obtained free as a by-product from a plant power house. Assume 50 per cent utilization of CO_2.

(e) The equipment will be run in a continuous, steady state condition. Then the growth area required is:

$$\frac{100\text{ tons}}{\text{day}} \left| \frac{2{,}000\text{ lb}}{\text{ton}} \right| \frac{\text{sq ft-day}}{0.01\text{ lb}} = 20{,}000{,}000\text{ sq ft or 434 acres.}$$

Compressor capacity required (to compress stack gases and diluting air to 30 psig distribution pressure):

$$\frac{200{,}000\text{ lb algae}}{\text{day}} \left| \frac{1.83\text{ lb } CO_2}{1\text{ lb algae}} \right. \times$$

$$\times \frac{1\text{ lb } CO_2\text{ compressed}}{0.50\text{ lb } CO_2\text{ utilized}} \left| \frac{12.75\text{ lb diluted gas compressed}}{1\text{ lb } CO_2\text{ compressed}} \right.$$

$= 776{,}000$ lb/hr, or 160,000 ft/min STP to be compressed.

Power requirements: (1) for circulation of media:

$$\frac{200{,}000\text{ lb algae}}{\text{day}} \left| \frac{0.0295}{0.01} \right| \frac{1.48\text{ kwh}}{\text{lb algae}} \left| \frac{\text{day}}{24\text{ hr}} \right. = 36{,}400\text{ kw.}$$

(2) for compressing gas:

$$\frac{200{,}000\text{ lb algae}}{\text{day}} \left| \frac{1.83\text{ lb } CO_2}{1\text{ lb algae}} \right| \frac{0.19\text{ kwh}}{\text{lb } CO_2\text{ compressed}} \left| \frac{\text{day}}{12\text{ hr}} \right. = 11{,}600\text{ kw.}$$

(3) for refrigeration:

$$\frac{200{,}000\text{ lb algae}}{\text{day}} \left| \frac{0.0295}{0.01} \right| \frac{2.87\text{ kwh}}{\text{lb dry algae}} \left| \frac{\text{day}}{12\text{ hr}} \right. = 141{,}000\text{ kw.}$$

Total major power requirement is approximately 200,000 kw.

Size of power plant necessary to provide the CO_2 requirement:

$$\frac{200{,}000\text{ lb algae}}{\text{day}} \left| \frac{1.83\text{ lb } CO_2}{\text{lb algae}} \right| \frac{\text{lb } CO_2\text{ provided}}{0.50\text{ lb } CO_2\text{ utilized}} \times$$

$$\times \frac{0.272\text{ kwh}}{\text{lb } CO_2} \left| \frac{\text{day}}{12\text{ hr}} \right. = 16{,}000\text{ kw.}$$

Growth Area — 20,000,000 sq ft @ \$2.00.* Land, prepare land, concrete pad, transparent cover, gas collection and distribution system, circulating pumps, media preparation equipment, harvesting equipment, drying and packaging equipment, warehouses, instrumentation, etc.	\$40,000,000
Compressor Station. Compressors, drives, filter, aftercoolers, silencers, building, etc.	6,000,000
Power House — 20,000 kw @ \$200. Boilers, turbines, generators, fuel storage, power distribution system, building, etc.	4,000,000
Refrigeration System — 150,000 standard tons. Cooling equipment, coolant, circulation system, etc.	5,000,000
Total Capital Expenditure	\$55,000,000

*Probably a low figure.

The annual fixed charges are then:

Depreciation	10%	\$5,500,000
Taxes	2	1,100,000
Insurance	2	1,100,000
Interest	3	1,600,000
Maintenance	5	2,800,000

	Cost/lb algae
Fixed charges per unit:	
$\frac{\$12{,}100{,}000}{\text{year}} \left\| \frac{\text{day}}{200{,}000\text{ lb algae}} \right\| \frac{\text{year}}{365\text{ days}}$	16.6¢
Raw materials cost:	
Carbon dioxide $2 \left\| \frac{0.14¢}{\text{lb } CO_2} \right\| \frac{}{0.5} \left\| \frac{1.83\text{ lb } CO_2}{\text{lb algae}} \right.$	1.0
Nitrogen	0.4
Other major nutrients	1.3
Micro-elements, water	0.1
Sub-total	2.8
Unit operation cost:	
Circulation $\frac{(1.48)\ (0.0295)}{0.01\text{ lb algae}} \left\| \frac{0.7¢}{\text{kwh}} \right.$ (power cost only)	3.0
Harvesting (including labor)	15.0
Drying (including labor)	5.0
Milling and packaging (including labor)	1.0
Sub-total	24.0
Labor not associated with above unit operations:	
Receiving, shipping, warehousing, media preparation, power plant operation, compressor station operation, refrigeration system operation, circulation system operation, laboratory, secretarial, supervision, general administration, etc.	4.0
Transportation of product	0.5
Sub-total	4.5
Total	47.9¢

CONCLUSION

The general requirements for an algae culture system for maximum growth can be summarized as follows:

(1) System should be designed so that the optimum amount of surface per unit of volume is exposed to the light source (sun).

(2) System should be designed so that the culture media is subjected to considerable turbulence.

(3) System should be designed so that the culture media can be continuously aerated and kept saturated with carbon dioxide.

(4) System should be continuous and so designed that

a constant number of cells will remain at all times.

(5) System should be designed so that average age of cells is kept constant.

(6) System should be designed so that concentration of nutrients in the medium will be constant at their optimum value.

(7) System should provide means for maintaining temperature of medium at constant value.

(8) System may have to be designed so that media can be sterilized and so that the entire process may be conducted under sterile conditions.

Very little work has yet been done on the recovery of the algal cells from the culture medium. However, the process should be relatively simple, though not necessarily inexpensive.

A *very rough* cost estimate has been presented showing that the cost of algae under extremely favorable circumstances would be about 50 cents per lb. It is believed the actual cost could well be over a dollar per lb. At this cost algae cannot hope to compete with soy bean meal and other similar products. (At present whole ground soy beans sell for 6 cents per lb.)

As a result of the conditions discussed in this report, it is believed that the large scale culture and recovery of algae for use as food, feed, or fermentation raw materials is not now economically feasible, nor will it be economically feasible in the near future.

In addition to the large initial plant cost it can be seen from the foregoing discussion that the cost of raw materials and the operating cost would also be substantial.

Because of these economic factors, it is believed that the mass culture of algae has only three possibilities of becoming a practical reality: (1) either the population of the Earth must increase to a point such that a new source of foods or feeds is mandatory regardless of cost, or (2) a major research break through must occur either in equipment design or the discovery of some algal species as yet unknown which exhibits greatly enhanced growth under less stringent conditions, or (3) the algae must be shown to be a source of some extremely valuable materials.

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THE PRODUCTION OF COLD BY MEANS OF SOLAR RADIATION*

By FELIX TROMBE AND MARC FOEX

Details of construction are given for a solar refrigerating apparatus developed at the Montlouis Laboratory. The refrigerator functions by means of an intermittent ammonia cycle in which the ammonia solution is directly heated by solar radiation. In prototype trials, daily production of ice was about 6 kgm.

In most of the arid regions there occurs, in general, a hot and dry climate, accompanied by an intense and regular insolation. In these zones, usually poor in energy resources, the production of cold by means of solar radiation can be of exceptional interest.

Various researches and accomplishments have already been made in this field; in particular, V. A. Baum, at Tashkent (Afghanistan, USSR), has constructed an assembly of solar refrigerators producing 250 kgm of ice a day. The necessary vapor for the functioning of the refrigerator proper is produced by a heater placed at the focus of a large paraboloid constantly orientated towards the sun.

We proposed, at the Laboratoire de l'Energie Solaire of Montlouis (Pyrénées-Orientales), to achieve a refrigerator functioning by means of an intermittent ammonia cycle, the ammonia solution being directly heated in the zone of concentration of solar radiation; such a cycle adapts itself well to the utilization of the rays of the sun. The ammonia solution is heated during the insolation and produces ammonia gas under pressure, which liquifies. The cold (distillation and redissolution of the ammonia gas) is produced after the setting of the sun and during the night. The first attempts, with a classic refrigerating apparatus coupled with cylindro-parabolic mirrors receiving and concentrating the solar radiation onto an east-west focal line, gave rather weak daily yields, the inertia of the apparatus being important. 30 to 35 kgm of ice are obtained from receiving about 80 kwh of incident solar energy. (Cylindro-parabolic mirror of 20 m^2, receiving 1 kw/m^2 and utilized during 4 hours.)

The expense of energy is therefore about 2.5 kwh per kgm of ice.

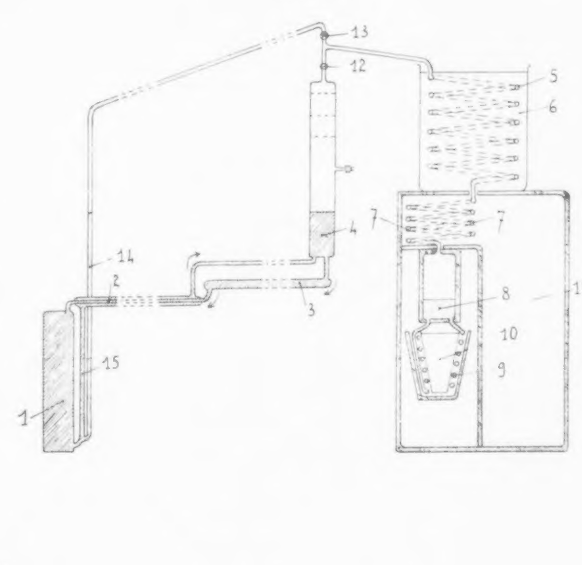
An important improvement has been obtained by the use of a refrigerating apparatus with weak thermal inertia and heat recovery, recommended by one of us.

Essentially, it consists of (Fig. 1): (a) a reserve vat (1), completely filled with ammonia solution, which must remain cold. The upper part of this vat contains, during the different phases of functioning, solutions richer in ammonia than those found in the lower part. This superposition can be stable, the weak solutions being more dense than the rich solutions; (b) a temperature exchanger (2); (c) a heating tube (3) on which is concentrated the solar energy; (d) a boiler (4) containing enough liquid to permit the distillation of the necessary quantity of ammonia gas; (e) a condenser (5) cooled by a reserve of water (6); (f) a reserve of liquid ammonia (8) surmounted by a coil (7) and communicating with another coil (9) surrounding an ice container (10); the assembly is contained in a cold chamber (11); (g) the valves or clappers (12) and (13).

During heating, valve (12) is open and valve (13) closed; the circulation of the ammonia solution is assured by the release of bubbles of ammonia gas on a level with the tube (3) and up to the boiler (4). The warm impoverished liquid coming from this latter exchanges its heat with the cold liquid drawn to the upper part of the reserve, then rejoins the bottom of this same reserve. The released ammonia gas passes through the condenser where it liquifies and rejoins, across the coil (7), the reserve (8) and the coil (9).

For the production of cold, after the suppression or disappearance of the solar heating, the valve (13) is open and the valve (12) closed. The intake of ammonia gas due to the cooling of the boiler (4) is effected by the tubes (14) and (15). The liquid-gas mixture in the tube (15) assures the general circulation of the ammonia solutions in the direction of the arrows. The cooling of the boiler is, by this fact, accelerated and the pressure

FIG. 1.



*Translation of the note which appeared, in French, in *Comptes rendus des séances de l' Académie des Sciences*, 242: 1000-3, séance du 20 février 1956.

lowered, instigating the distillation of the ammonia gas. This distillation takes place, in the beginning, in the assembly coil (9)-reservoir (8); but, this latter being isolated, its temperature is lowered, and the consumption of cold takes place then only at the level of the coil (9). The speed of distillation is a function, on one hand, of the speed of cooling of the ammonia solutions and, on the other hand, of the thermal requirements of the coil (9).

The advantages of the preceeding apparatus are:

(1) a weak inertia; a small part only of the ammonia solution being heated and the heat furnished, outside of that necessary for distilling the ammonia gas, being recuperated in the exchanger;

(2) an identical efficiency of refrigeration, from the beginning to the end of the absorption; the released gas always meeting the weakest solutions;

(3) a small difference between the temperatures of absorption and of distillation; this result is obtained thanks to the good absorption conditions and the presence of a cold reserve, the relative importance of which can be selected;

(4) a refrigeration without circulation of water, an indispensable condition in arid countries.

In our trials with a prototype of low power, the concentration of solar radiation is achieved with a cylindro-parabolic mirror of 1.5 m^2, orientated east-west and giving an effective heating time of 4 hours; a pre-heating at the beginning of the morning, at a reduced power, because of the inclination of the sun's rays, permits the attainment of the distillation system in a little more than an hour. The condenser and the cold reserve not surpassing 25° C, the temperature of the boiler can remain below 90°C, a value well below that used in the classic cycles. The daily production of ice is about 6 kgm, or obviously 4 kgm/m^2 for 4 hours of heating. If one does not take into account the pre-heating, which is relatively weak, it appears that the production of 1 kgm of ice consumes an incident solar energy of about 1 kwh.

WORLD RESEARCH ACTIVITIES

The following survey of world-wide solar energy activities is intended to supplement, for the years 1955 and 1956, the directory section in *Applied Solar Energy Research* (Stanford Research Institute, 1955), which covered research to December, 1954. As this survey will be a regular feature of the *Journal*, the editor will welcome any information on activities not mentioned below, or on future developments in the utilization of solar energy.

BELGIUM

Technique de la Chaleur. Cercle d'Etudes Inter-Ecoles. 7, Avenue du Vert Chasseur, Uccle.

Leon Crespin, *president-fondateur.*

Intends to establish a research center on applied solar energy for Belgium and the Congo, in Brussels. At present, seeking support of Belgian industrialists.

CANADA

University of Toronto. Dept. of Mechanical Engineering. Toronto 5.

E. A. Allcut; F. C. Hooper.

Engaged in experimental work on heat trap design factors and on preliminary design work for a solar house. Principal interest is in heat storage, particularly on an annual basis. Associated projects carried out in the analogue computation field in transient conduction, using hydraulic and electric models. Work on the heat pump now inactive.

Royal Military College. Kingston, Ontario.

J. W. Hodgins, (now with McMaster University, Hamilton, Ont.)

Studies on storage of heat as heat of fusion, including a completed study of Glauber's salt, and a search for a better hydrate. Some experiments on nucleating crystallization by means of plastic replicas. Program temporarily in abeyance.

ENGLAND

Building Research Station. Watford, Herts.

J. K. Page (now with the Nuffield Foundation, Division for Architectural Studies, London).

Collected material on availability of fuels and on sunshine statistics in centers in the British Colonial Territories, for possible use in an economic survey of solar energy utilization. Studied predictions of solar radiation on inclined planes in tropical regions. Prepared radiation tables covering latitudes 0 to 60 to provide a rapid technique for computing daily and hourly totals of radiation.

Electrical Research Association. Savoy Place, London, W.C.2.

E. W. Golding, *head of Rural Electrification and Wind Power Department.*

Concerned with the possibilities of combining solar energy with wind power and other local energy resources to supply the energy needs of isolated communities in under-developed areas.

Correction: *Applied Solar Energy Research,* p. 8. Miss M. V. Griffith is in charge of the Heating, Cooking and Allied Problems Department of the Electrical Research Association; she is not, as the text indicates, working under Mr. Golding's direction.

Imperial College of Science and Technology. Dept. of Mechanical Engineering. City and Guilds College, Exhibition Road, London, S.W.7.

Harold Heywood; D. Patel.

Concluded research on the generation of electricity by thermo-elements heated by direct solar radiation. Dr. Heywood has been appointed a temporary UNESCO technical expert to advise the Egyptian Government on solar energy research, with particular application to water distillation.

Rothamsted Experimental Station. Harpenden.

N. W. Pirie.

Continuing work on the extraction of protein directly from leaves, in order to make a product suitable for use as human food.

FRANCE

Centre National de la Recherche Scientifique. Centre de Physiologie Végétable. Laboratoire de Photosynthèse. Gif-sur-Yvette, S-O.

A. Moyse.

Studies on the nutrition of *Chlorella* and related unicellular algae cultivated for long periods of time on environments rich in mineral nutrients. Study of the variations of pH, of the influence of nitrogen sources in controlled and in out-door cultures. Trials on the pre-pilot scale over several sq meters. Other studies on the composition, growth, and photosynthesis of *Chlorella;* and photosynthesis in broad-leaved plants.

Centre National de la Recherche Scientifique. Laboratoire de l'Energie Solaire. Citadelle de Montlouis. Pyrénées-Orientales.

Félix Trombe, *director;* Marc Foex.

Recent activities include operation of 35 ft solar furnace and of 2 small furnaces, design of 1000 kw solar furnace, and design of other new equipment, including solar refrigerator and solar heating units for the fortress.

FRENCH WEST AFRICA

Institut des Hautes Etudes. Ecole Supérieure des Sciences. Dakar.

Henri Masson.

Completed study of domestic solar water heater, which is now being produced commercially. A 2 sq meter solar distiller will also be put on the market, for use in remote areas. Research on production of solar power and, later, on air cooling with solar energy is planned.

GERMANY

Botanisches Institut Freising-Weihenstephan. Technische Hochschule München. Freising-Weihenstephan.
Hans v. Witsch, *director.*

Investigating cellular changes in algae, the influence of environmental conditions on the growth of algae in mass cultures and analysis of the material composition of the algal mass.

Institut für Tageslicht-Technik. Robert-Haug-Weg 11, Stuttgart.

Friedrich Tonne, *director;* George Bacher; Egon Haller; Wilhelm Normann; Carl Pfotenhauer; Manfred Schmidt.

Studies include: (1) theoretical measurement of direct and diffuse solar energy; (2) heating effect of solar energy through windows; (3) influence of solar heat on inner room climate; (4) influence of high buildings on the insolation of neighbouring buildings; (5) experimental model of the Heliodon for measuring the penetration of solar energy; (6) sun protection methods; (7) full utilizations of solar rays in the sub-tropics.

Marburg, Universität. Physikalisch-Chemisches Institut. Marbacher Weg 15, Marburg.
H. T. Witt.

Studies on the primary process of photosynthesis and the photo-chemistry of pure chlorophyll and other dyes. Two methods have been developed to measure fast primary reactions and low concentrations of intermediates.

ISRAEL

Israel Institute of Technology. Solar Radiation Laboratory. Haifa.
N. Robinson.

Recent developments include (1) an occulting device for shading the pyrheliometer from the direct radiation of the sun; (2) a second type of the "insoloscope", first announced in 1953; (3) a registration device for "cooling power," registering the combined influence of direct and scattered solar radiation, air, temperature and wind on a blackened copper ball of 36.5°C; (4) an efficient, cheap flat collector.

Also made solar radiation measurements of various radiation elements for special purposes.

National Physical Laboratory. Research Council of Israel. P.O.B. 5192, Jerusalem.
H. Tabor, *director.*

Continued work on the chemistry and physics of selective black surfaces and simplified methods of their preparation. Carried out efficiency tests on flat plate collectors using these surfaces; results showed somewhat poorer performance than predicted and led to study of convection and radiation loss coefficients. Experiments in progress on a new flat plate collector for domestic applications. Start made on a simple concentrating collector for industrial production of steam at moderate pressure.

Studied possibilities of house cooling with solar energy, and intend to make an actual installation on a single-storey house during 1957. Built instrument for measuring solar absorptivities.

ITALY

Istituto de Merceologia. Universita degli Studi di Bologna. Piazza Scaravilli, 2, Bologna.
Giorgio Nebbia.

Preparatory work this winter on construction of small, highly-efficient plastic solar stills made with rigid sheets such as methyl methacrylate, and with a tray about 5 or 10 sq ft. Experimental work will begin next spring and summer.

JAPAN

Government Industrial Research Institute. Ministry of International Trade and Industry. Hirate-machi, Kita-ku, Nagoya.

Taro Hisada, *director;* Misao Mii, *head of mechanical division;* Nobuhei Hukuo, *chief of automatic control laboratory;* Choji Noguchi, *head of ceramic division;* Tetsuo Noguchi, *chief of solar research laboratory.*

Recent research work consists of: (1) design and construction of a solar furnace with aluminum paraboloidal reflector; (2) research with refractories, utilizing this furnace; (3) design of heliostat-type solar furnace with silver-coated glass reflector.

Noguchi Institute. 3569 6-Chrome, Itabashi-cho, Itabashi-ku, Tokyo.
Kenichi Oda, *director.*

Studies by Dr. Oda, Masatoshi Yamawaki and Takuya Ueda on the evaporation of sugar cane juice by solar heat. Studies by Yutaka Yamada, Iwao Ogura, Makoto Honda and Riki Johkura on the photochemical oxidation of furfural to maleic aldehyde acid utilizing solar radiation to form monosodium glutamate as final product.

Studies on solar evaporation of salt brine discontinued because most of the necessary data regarding field tests were obtained, and because test plants at Sakaide, Kagawa Pref. were destroyed by typhoon.

Yanagamichi, M. Consultant on Thermal Engineering. 7-536, Ebara, Shinagawa-ku, Tokyo.

Has Japanese patent on system of year-round air conditioning combining solar energy, nocturnal cooling, radiant panel system of heating and cooling and a heat pump, which has been installed in part of his residence.

NEW ZEALAND

Dominion Physical Laboratory. Private Bag, Lower Hutt.
C. J. Banwell; K. I. Williamson; L. Bastings.

Publicity and collection of data relating to solar water heating. Plan to set up a demonstration working model of a domestic solar water heater in Wellington.

Dominion Salt Ltd. Lake Grassmere, Marlborough.
P. J. Skellerup, *managing director.*

Continued production of salt from sea water by solar evaporation. Some experiments on spraying brine through the air to increase evaporization, and on the utilization of green dye in the crystallizing ponds.

SOUTH AFRICA

South African Council for Scientific and Industrial Research. National Mechanical Engineering Research Institute. P.O. Box 395, Pretoria.

Austin Whillier.

Main research projects are (1) program to analyze solar radiation data from all African stations and put in form convenient for use in designing solar energy collectors; (2) experimental investigation of the radiation-transmission properties of South African glass and of water and dyes; (3) study of the economic-optimum design of a domestic solar water heater for South African conditions, and of production techniques; (4) development of a small solar water heating unit that will form an integral part of the roof in low-cost housing; (5) design of a solar space heating and water heating system for installation in a private home. (Construction of the home has begun, and the Institute will carry out extensive tests and maintain records for several years); (6) investigation of solar stills for use in isolated communities and a study of the heat transfer occurring in a conventional solar still, to be followed by a study of the economic-optimum design of still under South African conditions; (7) survey of solar furnaces for high temperature research and plans for construction of furnace at Pretoria; (8) research on selective-radiation surfaces for solar collector, based on Tabor's work in Israel.

SWITZERLAND

Patek Phillippe. Research Laboratory. Grand-Quai 22, Geneva.

Georges Delessert, *manager;* A. Zibach; (late) J. M. Favey; A. G. Krassoievitch.

Made the following improvements in their self-winding photo-electric clock: (1) better accumulation of light energy by the system photovoltaic cell-micro-accumulator; (2) research on the 20 micro-ampere DC motor, and its manufacture.

UNITED STATES

Abbot, Charles G. Smithsonian Institution, Washington, 25, D.C.

Large solar steam generator, constructed by Dr. Abbot, to be tested at the University of Arizona. See his paper "Weather and Solar Variation" on page 3 for other investigations.

American Society of Heating and Air-Conditioning Engineers, Inc. Research Laboratory. 7218 Euclid Avenue, Cleveland 3, Ohio.

Clark M. Humphreys, *assistant research director.*

Sponsored work on solar energy utilization at the University of Minnesota (q.v.) under direction of R. C. Jordan.

Continued research on solar heat transfer through fenestration at the Research Laboratory. During summer rebuilt solar calorimeter. Work in progress on shading effects of awnings; work on plastic fenestration under consideration.

Arizona State College. Dept. of Physics. Tempe, Arizona.

Clement Kevane.

In 1956 installed a solar furnace of the 60-in. searchlight variety modified for use with a heliostat and automatic tracking system. Research is being conducted in the field of thermal properties of materials at high temperature.

Arizona State College. Rocky Mountain Forest & Range Experiment Station. Tempe, Arizona.

John P. Decker, *director.*

Laboratory for the study of transpiration and photosynthesis established in 1955 by the U.S. Forest Service. Studies are in progress or have been recently completed on CO_2 uptake and release, Kok-effect, Brown-effect, CO_2 compensation point, and estimating respiration in light.

Arizona, University of. Institute of Atmospheric Physics. Tucson 25, Arizona.

A. R. Kassander, Jr., *administrative director;* Reid A. Bryson; James E. McDonald.

Routinely measures the total solar radiation on a horizontal surface and the normal incidence solar radiation. Studies planned on the net solar radiation and its relationship to the heat budget of Arizona. A differential near-infrared solar spectrometer will be constructed to study temporal distribution of water vapor in the atmosphere.

Battelle Memorial Institute. 505 King Avenue, Columbus 1, Ohio.

No specific work on solar energy; however, some of their present research on semiconductor materials and on storage batteries may eventually be useful in solar batteries.

Bensin, Basil M. Agricultural Consultant. 1400 New Hampshire Avenue, N.W., Washington 6, D.C.

In co-operation with the Aluminum Company of America, conducting experiments with solar energy trapping devices in agriculture. Arranged tests in co-operation with various agricultural experiment stations to determine the efficiency of recent devices made of aluminum foil and plastic materials, which increase light intensity and raise soil temperature.

Bjorksten Research Laboratories, Inc. P.O. Box 265, Madison 1, Wisconsin.

Johan Bjorksten; Risto P. Lappala.

Conducted research program for development of plastic solar stills suitable for low cost production of fresh water from saline waters by solar evaporation, under contract for the U.S. Office of Saline Water.

Bridgers & Paxton. 213 Truman, N.E., Albuquerque, N.M.

In August 1956 completed solar heated office building, utilizing flat-plate aluminum collectors, which form the south wall of the building, and a 6,000 gal underground water tank for heat storage. Original conception and mechanical design by Messrs. Bridgers and Paxton; basic

design by John Miller; working drawings and improvements in basic design by Stanley and Wright; detailed calculations, equipment selection and some research by Roger Haines, chief engineer.

California, University of. Dept. of Agricultural Engineering. Davis, California.
General solar energy research by F. A. Brooks; research on solar heating of small homes by L. W. Neubauer; research on solar influences on domestic farm animal shelters by C. F. Kelly; studies on solar warming of paddy water for irrigating rice by C. R. Kaupke.

California, University of. College of Engineering. Mechanical Engineering. Berkeley 4, California.
Everett D. Howe.
Continuation of solar distillation experiments. In summer of 1956 preliminary experiments made on the use of paraffin wax as a material for absorbing and storing solar energy.

Clevett Engineering Laboratory. 34 Harwood Road, Natick, Mass.
M. Clevett.
Working under contract with American Thermos Products Co. of Norwich, Conn., to develop low cost portable solar cooking units for possible mass production.
Designed and constructed segmented-mirror solar furnace of approx. 3 kw capacity, mounted on a two wheel tractor. Limited production of this unit for sale to universities and industrial laboratories will begin in about one year. Will also initiate research on expendable solar-powered food warming and cooking devices for military and civilian use.

Colorado, University of. High Altitude Observatory, Boulder, Colorado.
Walter Orr Roberts, *director.*
Maintains basic research programs in solar physics and in sun-earth effects, and operates observational and data-reporting program of daily indices of solar activity based on coronagraphic observations. Recently initiated program of privately-sponsored research under its Institute for Solar-Terrestrial Research into solar-weather effects and solar influences on earth magnetism and the upper atmosphere.

Conn, Willi M. 6312 Indiana Avenue, Kansas City 30, Missouri.
Consulting work in design and construction of solar furnaces in the U.S. and abroad. Designed improvements now under construction for research work at very high temperatures using solar energy, where tests are performed in controlled atmospheres.
Studied rates of reactions at very high temperatures using 60-in. solar furnaces. Special interest devoted to refractory bodies of the alumina-silica systems for use at high temperatures, where rates of melting and freezing were studied. Construction of additional solar furnaces undertaken by the WMC Precision Works, Kansas City, based on Conn's designs, under direction of J. P. Robertson.

Contour Company. 3162 North Rosemead Blvd., Rosemead, California.
Dan Marvosh, *owner.*
Building a roof-mounted solar collector for research in long storage of high temperature heat. If proven feasible, a solar heated house will be built by the company in southern California.

Convair. San Diego 12, California.
B. I. Davis.
Activity in the field of high temperature material research using solar furnaces continued to summer of 1955, when Air Force sponsorship was withdrawn. In the latter part of 1956 one of the Air Force Searchlights was purchased, and plans made to reactivate solar furnace work in the future.

Desert Sunshine Exposure Tests. 7740 Ramona Road, Phoenix, Arizona.
C. R. Caryl, *director;* G. A. Leeper.
Current work includes the daily measurement of total solar radiation at 45° to the south, direct and under glass, as well as measurement of intensities of radiation at different hours of the day; determination of per cent ultraviolet in total radiation; co-operation with the Amer. Association of Textile Colorists and Chemists in testing fading rates of dyes; measurement of radiation and fading rates of colors on a moving rack that maintains normal incidence to the sun's rays.

E. I. DuPont de Nemours & Company. Engineering Dept. Wilmington 98, Delaware.
Some interest in experiment and development of solar distillation, solar heat traps, solar reflectors for intermediate and high temperature, and silicon as a material for solar batteries.

Edison Electric Institute. Joint AEIC-EEI Heat Pump Committee. 420 Lexington Avenue, New York 17, N.Y.
Issued reports on chemical heat storage and on the possibilities of a combination solar-heat pump unit, based on committee-sponsored investigations by G.O.G. Löf.

Edmondson, W. B. 227 Begonia Street, Oceanside, California.
Designed large-scale solar sea water conversion and/or power generation plants. Investigated possibility of modifying these plants to produce daily thunderstorms for smog elimination. Experiments with aluminum foils and metallized plastic films as reflecting surfaces for large, low-cost concrete, honeycomb and other paraboloids.

Florida, University of. College of Engineering. Gainesville, Florida.
Erich A. Farber, *director of solar energy research work.*
Investigations by Prof. Farber on solar hot water heating, house heating, power and solar furnaces; by B. D. Bennet on concentrating absorbers and solar refrigeration; and by W. H. Bussel and J. H. Smith on solar distillation.
Experiments are underway with dual circulation water heating systems, one circuit at atmospheric pressure; with absorption refrigeration units; parabolic concentrators,

cylindrical parabolas both moving and stationary, plastic solar stills; and a surplus search-light furnace used in high temperature studies, including the stability of different phases of materials used in the atomic energy field.

Fordham University. Dept. of Chemistry. High Temperature Laboratory. New York 58, N.Y.

Tibor S. Laszlo, *director.*

In 1955 constructed a 60-in. diameter solar furnace; designed and built an electronic guiding mechanism for altazimuthally mounted mirrors. Performed investigations on ZrO_2 and TiN systems.

During 1956, designed and prepared the construction of a 120-in. polar mounted solar furnace, measured performance characteristics of the 60-in. furnace and developed a sample holder for three directional positioning.

General Electric Company. Electronics Division. Electronics Park, Syracuse, N.Y.

Edward Keonjian; James O'Hern.

Developed pocket-sized, solar-powered radio receiver capable of working more than 8 months in total darkness without recharging, and weighing 10 oz. No plans for immediate production.

Hoffman Electronics Corporation. Applications Engineering Division. 3761 South Hill Street, Los Angeles 7, California.

Norman Regnier, *division manager;* Lawrence J. Schmidt; R. Schroter; S. D'Anna; D. Kefes; R. Yasui; C. Abeli; B. L. Birchard.

Developed a number of devices powered by solar cells, including a flashlight, highway flasher, a 400-cell "Big Bertha" solar converter which automatically tracks the sun to give optimum power conversion, and a number of portable radios. At present, constructing solar-powered air-sea rescue equipment operating in the 100-200 megacycle frequency range.

Hoffman Electronics Corporation. Semiconductor Division. (National Semiconductor Products). 930 Pitner Avenue, Evanston, Illinois.

D. C. Dickson, *chief engineer;* M. B. Prince, *director of research and development;* B. Ross; N. Wolf; E. L. Ralph.

Major work is in research, development, and production of silicon solar energy converters. New cells have an average efficiency of 9 per cent, with some as high as 14 per cent. Several types of cells available commercially.

Holloman Air Development Center. Holloman, N.M.

Paul D. Jose, *directorate of research and development;* Raymond Bliss, *directorate of ballistic missile test.*

Conducting studies on design and performance of solar furnaces. In progress are detailed studies of condensing mirrors which are composed of non-parabolic segments of various curvatures, and an exact solution of the energy distribution at the focal spot of a parabolic mirror.

International Rectifier Corporation. 1521 East Grand Avenue, El Segundo, California.

J. T. Cataldo and Harry Nash, *applications;* John Sasuga and Robert D. Hancock, *production and research.*

Development and production of large area selenium photovoltaic cells and silicon diffused junction semiconductors for efficient conversion of solar energy to electrical energy. Solar energy converters are in production and available for industrial applications.

Jet-Heet, Inc. 152 Van Brunt Street, Englewood, N.J.

Maria Telkes, *director of solar developments division*

Developed solar-powered thermopump, now being adapted commercially. Newly-formed division under Dr. Telkes will specialize in heat storage chemicals and thermoelectric materials, and commercial applications of solar energy in heating, cooling, pumping, power and distillation.

Charles F. Kettering Foundation. Box 215, Yellow Springs, Ohio.

H. A. Tanner, *director of research.*

Studied the mechanism of photosynthesis and the photochemistry of dyes and pigments.

Libbey-Owens-Ford Glass Company. Research and Development Depts. 1701 East Broadway, Toledo 5, Ohio.

Research related to flat-plate solar energy collector design, on transmission through ordinary and coated glass surfaces. During 1956, co-operated with Michigan State University by furnishing glass and consultation on a solar energy project investigating heating of barns, drying of hay, etc.

Arthur D. Little, Inc. 30 Memorial Drive, Cambridge 42, Mass.

Peter E. Glaser.

Built 5 ft searchlight furnace with precision controls, which is being used for high temperature metallurgical investigation.

Long, Vinton F. Engineering Consultant. P.O. Box 592, Shreveport, Louisiana.

Patent pending on a reinforced plastic parabolic reflector. Work on the fabrication of inexpensive solar cookers using pressed paper pulp parabolic shapes, coated with aluminized Mylar.

Mellon Institute of Industrial Research. University of Pittsburgh, Pittsburgh 13, Pennsylvania.

Robert Gardon.

In the past year investigated the manufacture of inexpensive, large concave mirrors suitable for incorporation in solar furnaces. Major work has been on the heating by radiation of transparent materials.

Minneapolis-Honeywell Regulator Company. Research Center. 500 Washington Avenue South, Hopkins, Minnesota.

Solar energy project inaugurated in summer of 1956, based on the idea of combining a low-temperature collector with a concentrating mirror to reduce collection losses. Dr. R. G. Nevins of Kansas State College made experimental measurements with a 5-ft diameter searchlight reflector equipped with a 6-in. diameter flat-plate collector, and noted collection efficiencies.

The company also has co-operated with MIT on the

control system of their solar heated house, and with the University of Illinois on their solar heating project.

Minnesota, University of. Dept. of Mechanical Engineering. Minneapolis, Minn.

R. C. Jordan; J. L. Threlkeld.

Research program on flat-plate collectors in progress, including a fundamental study of heat transfer from collector plate to fluid and an experimental program on collectors operating under controlled conditions.

Other studies include a research program on solar radiation incidence; availability of solar radiation in the upper Midwest and its potential utilization in heating buildings; and the use of solar radiation for the drying of farm products such as grain.

RCA Laboratories. David Sarnoff Research Center. Princeton, N.J.

Irving Wolff, *vice president, research.*

Investigating solar converters consisting of a p-n junction between 2 semiconductors or a junction between a semiconductor and a metal, for the direct generation of electricity (under contract with U.S. Signal Corps). Results have been obtained in the following areas: (1) determination of the best materials for such converters; (2) search for improved and cheaper methods of producing large area devices of this nature; (3) study of the stability of solar batteries under the action of sunlight and other types of radiation.

Reynolds Metals Company. Richmond, Virginia.

C. E. Burley, *supervisor.*

Conducted a limited program on solar energy applications, including a study of solar cookers based on developments by Maria Telkes and a study of methods of treating aluminum surfaces to increase their emissivity. Under consideration is the construction of a solar furnace.

Solar Energy Corporation of America. 103 Park Avenue, New York 17, N.Y.

Martin Weber, *president.*

Formed to explore commercial possibilities of solar energy. Plan to invest capital in developments in the U.S. and abroad.

South Florida Test Service. 4201 Northwest 7th Street, Miami 34, Florida.

Earl M. DeNoon, *owner and technical director.*

Work on the measurement and recording of solar radiation, direct and under glass 45° facing south, and on the effects of sunlight exposure on various materials and products, for clients of the organization.

Stanford Research Institute. Stanford Village, Menlo Park, Calif.

Rudolph Marcus; Kenneth Sancier; N. K. Hiester; Norman Fishman.

Studies of electron transfer, chemical conversion of solar energy, photogalvanic cells and solar furnace design.

Texas, University of. Dept. of Zoology. Austin 12, Texas.

Jack Myers.

Currently engaged in 2 related projects on the large-scale culture of algae under sunlight illumination: (1) measurement of efficiency of light conversion by *Chlorella* at low light intensity, i.e. maximum efficiency; (2) measurement of the efficiency of light utilization by *Chlorella* and other algae of the very high intensities of full sunlight.

U.S. National Bureau of Standards. Dept. of Commerce. Washington 25, D.C.

Ralph Stair; S. Zerfoss.

Investigation of the use of a solar furnace to produce high temperatures (Dr. Zerfoss). Measurements of the spectral energy distribution of direct solar radiation at Sacramento Peak, N.M. (Mr. Stair and others). Completion in June 1956 of the second unit of Mauna Loa Observatory (Hawaii), where solar radiation measurements will be made.

U.S. Office of Saline Water. Dept. of the Interior. Washington 25, D.C.

David S. Jenkins, *director;* W. Sherman Gillam, *chief of research branch;* Joseph J. Strobel, *chief of engineering and development branch.*

Stimulates private interest and research in solar distillation by exchanging and coordinating work in that field, cooperates in an international project in Algeria (under Organization for European Cooperation), and carries out actual research through federal grants and contracts. 1955-56 contracts related to solar energy under the Saline Water Conversion Program are: (1) use of plastics in solar stills (Bjorksten Research Labs.); (2) new methods of solar distillation (New York University); (3) design and evaluation of solar distillation units and design of pilot plant (G.O.G. Löf).

U.S. Snow, Ice & Permafrost Research Establishment. Corps of Engineers, U.S. Army. 1215 Washington Avenue, Wilmette, Illinois.

R. W. Gerdel, *chief of climatic and environmental research branch;* M. Diamond; Howard Reiquam.

Continued global and long wave radiation studies on the Greenland Ice Cap in the summer of 1956 by Messrs. Diamond and Reiquam. Dr. Gerdel extended previous studies with solar energy converters in the Arctic to include both the silicon and selenium type cells. Reports in preparation on both topics.

U.S. Weather Bureau. Dept. of Commerce. Washington 25, D.C.

Sigmund Fritz; Norman Foster; Laurence Foskett; T. H. MacDonald.

Primarily devoted to improvements in the precision of field measurements of radiation, including (1) improved techniques for calibration of pyrheliometers in an integrating sphere; (2) an integrating mechanism which is read once a day for radiation totals, now in operation at a number of field stations; (3) an improved normal-incidence polar mounting; (4) an improved photo-electric sunshine switch; (5) investigation of the influence of cosine-response and ambient temperature on output of the Eppley pyrheliometer in connection with IGY activities in high latitudes; (6) fabrication of a sky-brightness me-

ter for use in investigating "white-out" conditions in the Antarctic.

Dr. Fritz made an analysis of the solar radiation data from the Arctic Ice Island, T-3, and a theoretical study of the polar white-out.

U.S. Weather Bureau. Office of Climatology. Dept. of Commerce. Washington 25, D.C.

H. E. Landsberg, *director.*

Interested in making solar radiation data widely available; also, to a small extent, in crop-weather relations and problems of health as related to sunshine. The Office has published a sunshine map of the world, and regularly issues solar radiation data in the *Climatological Data National Summary.*

Utah, University of. Dept. of Experimental Biology. Salt Lake City, Utah.

John D. Spikes; Richard Van Norman.

Studies on various aspects of photosynthesis. A number of studies published on the photochemical activity of isolated chloroplasts and other topics.

Wisconsin, University of. Madison 6, Wisconsin.

John A. Duffie, *solar energy laboratory;* Farrington Daniels, *dept. of chemistry;* G. A. Rohlich, *hydraulic engineering laboratory;* V. E. Suomi, *dept. of meteorology;* G.O.G. Löf, *consultant* (Denver).

The following topics are being studied: solar refrigeration (Raymond Chung and D. A. Williams); photochemical methods for storing solar energy (Otto Neuwirth); use of plastics (R. P. Lappala); radiation recording instruments (Peter Schoffer); chemical methods of heat storage (G. C. Blythas); selective radiation coatings and solar refrigeration (Ihab Salam).

Development of two simplified, 1 hp steam engines undertaken by two small companies in Wisconsin.

First priority given to development of plastic solar cookers, which are being sent to Mexico for field tests. Other major work on absorption refrigeration, with units tested in Wisconsin and Denver.

In work on the fabrication of various plastics for cookers and reflectors, 2 reflectors of 8 and 12 ft diameters under construction. Some attention given to preparing crude concave, spherical mirrors made from plaster, concrete or wood, scooped out with a pendulum tool and then covered with aluminum foil or aluminized *Mylar.*

Simple integrating radiation meter developed (Prof. Suomi). Some study of solar radiation data collected over past 38 years in Madison and of special weather data from Mexico.

More emphasis on solar engines, reflectors and collectors planned.

Wright Air Development Center. Air Research and Development Command. United States Air Force. Wright-Patterson AFB, Ohio.

Leland L. Antes; R. G. Wheeler; L. C. Greene; W. Heintz; D. C. Reynolds.

Work related to the photovoltaic effect in CdS crystals, including: (1) improvement of crystal-growing technique, making large area cells feasible; (2) determination of the nature of the barrier layer; (3) purification of CdS powder by sublimation techniques and by doping with small quantities of impurities such as indium to obtain the required resistivity; (4) investigation of the ultimate purification of CdS; (5) some work on polycrystalline cells, by which large areas can be made relatively cheaply.

SOLAR ABSTRACTS

This section brings to the attention of our readers some of the important books and papers on solar energy which have appeared since the publication of the bibliography-directory ***Applied Solar Energy Research*** (***December,*** 1954). Papers in the ***Proceedings of the World Symposium on Applied Solar Energy*** have not been included, as most of our readers are already familiar with these. Wherever possible, authors' abstracts have been used; abstracts not designated as by the author are by the editorial staff of the *Journal*. Photocopies of papers abstracted below may be obtained at cost (10¢ per page) by members of the Association for Applied Solar Energy, from the Association's library at Phoenix.

* * *

AEIC-EEI Heat Pump Committee. "Possibilities of a combination solar-heat pump unit; a report... based on an investigation by Dr. G. O. G. Löf, September 1955." *Edison Elec. Inst. Bull.* 24: 77-80+. March 1956.

Results of investigations, sponsored by the committee, on the possibility of combining a heat pump unit and a solar energy collector for space heating and cooling. The amount of solar energy available for roof-mounted collectors 150, 300 and 500 sq ft in area was determined from climatological data for Columbus, Ohio, for January 1953 and January 1954. Dr. Löf prepared a preliminary engineering analysis of various proposed combinations of solar collectors, of the sizes listed above, in conjunction with heat storage systems and a heat pump unit; several of these combinations are illustrated diagramatically, and evaluated. Results of his study of the operating characteristics of a heat pump alone as compared with the combination of heat pump and solar collectors of the indicated sizes are tabulated. For each arrangement, the total system kwh use, performance factors and load factors are shown. Results of the study are not conclusive, but indicate that a heat pump system using solar energy exclusively would be impractical because of the large heat storage requirement. Illustrated.

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Ayres, Eugene. "The fuel situation." *Sci. Am.* 195(4): 43-49. October 1956.

A detailed analysis of predictions that the end of the fossil fuel era is close at hand. Curves of petroleum supply and demand for the U.S. and the world as a whole, based on reserve estimates of Lewis Weeks, indicate that U.S. production will begin to decline about 1965 and world production by 1980, while demand continues to rise. Natural gas production shows a similar decline beginning between 1965 and 1970, and shale oil or oil from tar sands are not expected to affect the supply greatly. Coal demands are likely to increase, causing production to rise at about 3 per cent per year by 1960, and reach a peak in 1970, when it too will decline. The fuel situation necessitates not only the development of new sources of energy, but more efficient utilization of present energy sources in space heating and transportation. Nuclear power, converted directly to electricity, will reduce the depletion of our reserves, particularly for space heating, which consumes one half our fuel. In respect to our second largest use of energy, land transportation, because supplies of liquid fuel for internal combustion will soon be inadequate even for our present population, development of more efficient engines is likely. Illustrated.

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Baum, V. A. "The use of solar energy." *J. Sci. Indus. Res.* (New Delhi) 14A(8): 365-73. 1955.

A summary of experiments conducted by the Krzhizhanovsky Power Institute of the Academy of Sciences, USSR, in the field of solar energy, and of conclusions drawn from operations of and calculations for installations in the sunny regions of the Central Asian Republics. The following installations are discussed: solar heaters of the hot-box type for water heating and for distillation; cookers and boilers, including an experimental steam generator with a paraboloid mirror of 80 sq m, which produces 50-60 kg steam per hour; a regenerative 3-step distiller; an absorption refrigerator producing 250 kg of ice per day; solar house heating; solar power installations; and high-temperature furnaces. Illustrated.

* * *

Benveniste, Guy, and Hiester, Nevin K. "The solar furnace... new tool for high-temperature work." *Mech. Eng.* 78(10): 915-20. October 1956.

Review paper covering the following aspects of solar furnaces: historical background; basic operating principles, including concentration ratio and concentration efficiency of parabolic-type furnaces, actual furnace efficiency, temperatures obtainable in such furnaces, and the physical arrangements of apparatuses for (1) tracking the sun, (2) heating the target, and (3) controlling temperature and flux. Several modern solar furnaces are described, including those at Mont Louis, Bouzareah in Algeria, and the California Institute of Technology. Illustrated.

* * *

Black, J. N. "The distribution of solar radiation over the earth's surface." *Arch. Meteor. Geophys. Bioklimatol.* B, 7(2): 165-89. 1956.

Records of total solar radiation measured on a horizontal surface *(Q)* on a monthly basis and of more than 3 years' duration are available for 88 stations. The stations are mainly concentrated in North America and Europe, and it is not possible to determine the global distribution of radiation directly from these records. Solar radiation and mean cloud amount *(C)* were therefore related by the quadratic regression $Q = Q_A\ (0.803 - 0.340\ C - 0.458\ C^2)$, where Q_A is the maximum possible radiation in the absence of an atmosphere (Angont's values) and the values of C were obtained from the maps printed in Shaw's *Manual of Meteorology*.

Using the known distribution of Q_A and C, values of Q were calculated by use of the equation above for each 5° intersection of latitude and longitude over land, and for each 10° intersection over sea. Isopleths of Q for each successive 50 gcal/cm²/day are shown on the 12 monthly maps on which the distribution of radiation over the earth's surface is illustrated. Attention is drawn to certain features of these maps, in particular to the occurrence and movement of zones of high radiation, and a comparison is made of estimated and recorded radiation for 12 stations. 14 figures. (author's abstract)

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Calvin, Melvin. "The photosynthetic carbon cycle." *J. Chem. Soc.*: 1895-1915. June 1956. (Centenary lecture to the Chemical Society at the Institution of Chemical Engineers, London, October 20, 1955.)

The nature of the photosynthetic carbon cycle is now known; it has been carried out in its entirety in the absence of living materials and formed parts of living cells. This discussion (dealing mainly with work by the author and his associates at the Univ. of California Radiation Lab.) is divided into two sections: (1) a description of the set of transformations which the carbon atom of CO_2 undergoes on its way from CO_2 to carbohydrate; (2) a description of the state of our knowledge of how the electromagnetic energy which is captured by the chlorophyll in green plants is used to accomplish that series of transformations, since the series of transformations — CO_2 plus water to give carbohydrate and oxygen — is an upgrade one, i.e., one in which energy is stored. That energy must ultimately come from the electromagnetic radiation absorbed by the chlorophyll. Illustrated. (author's summary)

* * *

Campbell, I. E., *ed. High-Temperature Technology.* Sponsored by the Electrochemical Society, Inc., New York.

VOL. 1 1957

N.Y., J. Wiley, 1956. 526 pp.

This monograph, consisting of contributions from some 35 authorities in the field, summarizes recent developments in the techniques and materials of high-temperature technology. It is divided into four sections: an introductory section tracing the development of modern refractories and modern high-temperature techniques; a materials section, dealing with metallic and non-metallic refractory materials and cermets; a methods section, discussing sintering and various types of high-temperature furnaces; and a measurements section, presenting a discussion of temperature measurements and the testing of physical and mechanical properties. Solar furnaces are considered in a brief paper in the methods section: "Obtaining very high temperatures by solar furnaces", by W. M. Conn. This deals with quantitative heating tests with solar furnaces, the design of experimental solar furnaces, and possible industrial applications and fields of study. A table gives design data for several modern solar furnaces. Illustrated, with author and subject indexes.

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Foster, Norman B. and MacDonald, T. H. "Silver disk pyrheliometry simplified." *Monthly Weather Rev.* 83 (2): 33-37. February 1955.

The following devices for simplifying the operation of the Abbot Silver Disk Pyrheliometer are described: (1) an automatic shutter; (2) a simplified heating and cooling timing sequence, and (3) an improved method of reading the pyrheliometer thermometer. The authors also describe their experience in automatically recording the silver disk temperature by means of a thermocouple, amplifier, and recorder. Illustrated. (authors' abstract)

* * *

Fritz, Sigmund. "Weekly mean values of daily total solar and sky radiation: supplement no. 1." *U.S. Weather Bureau, Technical Paper* 11. 1955. 4 pp.

This supplement brings up-to-date the paper by I. F. Hand (Technical paper 11; AFASE no. 2764) by the addition of data from five new stations — Phoenix, Ariz.; Charleston, S.C.; El Paso, Tex.; Rapid City, S. Dak.; and San Antonio, Tex. — each of which has records for approximately five years. Illustrated.

* * *

Gomella, Cyril. "Le problème de la démineralisation des eaux saumâtres par distillation solaire." *Terres et eaux* 6(25): 4-31. 2e trimestre 1955. (The problem of the demineralization of saline water by solar distillation.)

This article outlines the main points of the program of research established by the Service de la Colonisation et de l'Hydraulique of Algeria as regards the use of solar energy for the distillation of water, research that took place between the end of 1953 and the spring of 1955. For the present, these researches have been applied to the Saharan regions. Theoretical possibilities of the use of solar energy for desalting water are stated, and reasons given for the use of an apparatus of the "Verriere" type (glass-covered tank) to carry out the experiments.

The second part of the article summarizes results already obtained. It has been possible (1) to draw and build a typical apparatus, which is already in use in various regions of the Sahara, to supplying drinking water and other private needs; (2) to define the methods of exploitation, i.e., to suppress the bad taste of distilled water and the saline crystallizations which encrust the apparatus. The average possibilities of these "Verrieres" have been determined.

The author compares from an economic point of view the processes of demineralization by ion-exchange, distillation by vapor-compression, and solar distillation. Solar distillation is particularly well-adapted to supply drinking water to small villages and isolated dwellings. The price of electric power and of transportation being very high in Saharan regions, it is important to use an apparatus which is neither heavy, brittle nor cumbersome, and consumes no electricity. Illustrated. (author's abstract)

* * *

———"Démineralisation des eaux saumâtres par distillation solaire." *Ibid.* 6(26): 10-13. 3e trimestre 1955. (Demineralization of saline waters by solar distillation)

A continuation of the above article, giving results obtained after April 1, 1955, in Algerian experiments. Results show that: (1) in Saharan regions it is possible to store demineralized water to make up for the irregularity of water production in various seasons; (2) the two-slope apparatus is more efficient than the one-slope apparatus; (3) a flat shape is best; (4) the thermic isolation of the bottom of the basin is very important; (5) the north and south faces have more or less the same efficiency; and (6) the influence of reflectors is greatest in the winter. (author's abstract)

* * *

Guillemonat, A. "Le four solaire de 50 kw de la Bouzareah." *Industries et travaux d'outre-mer* 3(23): 614-18. October 1955. (The 50 kw solar furnace at Bouzareah).

A description of the solar energy utilization program undertaken by M. Frixon and the author in Algeria, and its present state of achievement. Possible methods of utilization were considered, employing the heat of the sun directly, or transforming it into mechanical or chemical energy. Production of high temperatures by concentration was decided upon, and, for this purpose, a solar furnace was constructed, of the mobile, paraboloidal mirror type, with no auxiliary heliostat. The 50 sq m mirror surface is made up of 144 separate elements. The furnace attains a temperature of about 3000° C, with a power of about 50 kw. Research possibilities for the furnace are outlined. Illustrated.

* * *

Haines, Roger. "Solar collector and heat pump heats, cools new office building." *Heat Pip. Air Cond.* 28(10): 104-107. October 1956.

The first commercial building in the U.S. to be completely heated and air conditioned by solar energy was recently finished in Albuquerque, N.M. by the firm of Bridgers and Paxton. This article describes the heating and cooling system in detail: essentially it consists of a 830 sq ft sloping, flat plate collector which forms one wall of the building, a 7½ ton water chiller which is used as a heat pump in winter and for cooling in summer, a 6000 gal water tank for heat storage, an evaporative water cooler, pumps, and distribution system. Data obtained from the design and operation of this building will be valuable in planning future solar-heated buildings. Illustrated.

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Hisada, Taro *et al.* "Solar furnace: its construction and performance." *Mem. Govt. Ind. Res. Inst.* (Nagoya) 2. August 1956. 26 pp. (In Japanese, with English abstract.)

The process of construction and the results of the initial inspection test of the first Japanese solar furnace are related in this paper. Based on a design by W. M. Conn, without the auxiliary heliostat, the furnace has an aluminum paraboloidal mirror with an aperature of 2 m. Further development work on the utilization of the solar furnace is planned. Illustrated.

* * *

Hodgins, J. W. and Hoffman, T. W. "The storage and transfer of low potential heat. I. Glauber's salt as a heat storage material." *Can. J. Technology* 33(4): 293-302. July 1955.

A study has been made of the variables affecting the storage of low potential heat as the heat of fusion of Glauber's salt. The geometry of the container was determined as the result of preliminary experiments, using a moving transfer surface. Extensive experiments with the final design yielded the following information: (a) low over-all efficiency is the result of segregation of phases as crystal growth proceeds; (b) short heat paths in the exchanger are essential to keep thermal resistance at a minimum; (c) the crystal growth rate in this system is the rate-governing process once phase isolation has occurred; (d) over-all heat transfer coefficients are in the order of 2 Btu/hr (sq ft) (°F). Illustrated. (authors' abstract)

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Jordan, R. C. and Threlkeld, J. L. "Laboratory for solar

energy study at Minnesota." *Heat. Pip. Air Cond.* 28 (5): 143-47. May 1956.

A description of the special laboratory facilities constructed at the University of Minnesota to study solar engineering. The nature of the problems is outlined. Also contains a description of some of the projects now in progress and outlines some of those planned in the future. Illustrated. (authors' abstract)

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Laszlo, Tibor S. "Solar furnace in high-temperature research." Science 124(3226): 797-800. October 26, 1956.

In the field of high-temperature research, solar furnaces are superior to the conventional type furnace with regard to temperatures obtainable, absence of combustion products and other contaminants, and ease of observation and measurement. The operating principles of a solar furnace are here outlined, and the Fordham University solar furnace, constructed from a 5 ft searchlight, is described in detail. Research which could be, or has already been carried out in a solar furnace is outlined, including determination of physical constants above 2000° C, and growing crystals of refractory oxides. Illustrated.

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Loferski, Joseph J. "Theoretical considerations governing the choice of the optimum semiconductor for photovoltaic solar energy conversion." *J. App. Phys.* 27(7): 777-84. July 1956. (Paper presented at the Tucson Conference on Solar Energy — the Scientific Basis, October-November, 1955)

The theory of the photovoltaic effect is used to predict the characteristics of a semiconductor which would operate with optimum efficiency as a photovoltaic solar energy converter. The existence of such an optimum material results from the interaction between the optical properties of the semiconductor, which determine what fraction of the solar spectrum is utilized, and its electrical properties, which determine the maximum efficiency of conversion of electricity. Considerable attention is devoted to the effect of the forbidden energy gap (E_G) of the semiconductor. It is shown that atmospheric absorption causes a shift in the solar spectrum which changes the value of the optimum forbidden energy gap between the limits of 1.2 ev $< E_G <$ 1.6 ev. Furthermore, plausible departures of the diode reverse saturation current (I_0) from the parametric dependence predicted by Shockley are considered, and it is shown that such departures reduce the advantage of the optimum material over others in the range 1.1 ev $< E_G <$ 2.0 ev. The relation between E_G and the load impedance for maximum power transfer from the solar energy converter is discussed. Finally, I_0 is computed from the published values of the semiconductor paramters of 3 intermetallic compounds, i.e., InP, GaAs and CdTe, and it is shown that the efficiences predicted for these materials are greater than those predicted for other materials which have been proposed, i.e., Si, CdS, Se and AlSb. (author's abstract)

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Marcus, Rudolph J. "Chemical conversion of solar energy." *Science* 123(3193): 399-405. March 9, 1956.

A discussion of the possibilities of storing solar energy as potential chemical energy. As a background, the photosynthetic process in green plants and the Hill reaction are reviewed; and the actual process of conversion from solar energy to chemical energy is considered in terms of electron-transfer spectra. After examining criteria for practical chemical conversion systems, the author concludes that one of the best energy-storing reactions is the photoreduction of water resulting in the production of hydrogen. Various paths for the photochemical hydrogen production are described, and it is shown that in each case, production of hydrogen depends on the cyclic oxidation and reduction of a photocatalyst. It is concluded that the chemical conversion of sunlight avoids some of the thermodynamic problems inherent in the black-body degradation of solar energy.

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Morse, R. N. "Solar water heaters for domestic and farm use." *CSIRO Engineering Section Report* E.D.3. Melbourne (Australia), July, 1956. 14 pp.

A solar water heater is described having an output of 45 gal of hot water per day suitable for domestic or farm use. Complete details in the form of drawings, materials lists, and photographs are included, together with an account of the problems met in actual installations. Performance and operating costs under Melbourne conditions are discussed briefly. This report largely supersedes *CSIRO Central Experimental Workshops Report* E.D.1. "The design and construction of solar water heaters." April 1954; rev. February 1955, by the same author. (author's abstract)

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Nebbia, Giorgio. "Un nuova tipo di distillatore solare." *La Ricerca Scientifica* 25(6): 1443-46. June 1955. (A new type of solar still.)

Design and characteristics of a new type of solar still are described and the results obtained during the first months of its operation are reported. Illustrated. (author's abstract)

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Prince, M. B. "Silicon solar energy converters." *J. App. Phys.* 26(5): 534-40. May 1955.

Theory is given for the design of silicon solar energy converters commonly known as the Bell Solar Battery. Values are given for the various parameters in the design theory. Experimental data are presented and compared with the theoretical relations based on a simple model.

It is found that with present techniques, units can be made with up to 6 per cent efficiency in the conversion of solar radiant energy to electrical energy. An important factor in obtaining such high efficiencies is the reduction of the series resistance of the cell to as low a value as possible. (author's abstract)

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Rabinowitch, Eugene I. *Photosynthesis and Related Processes. Vol. 2, pt. 2: Kinetics of Photosynthesis (Continued); Addenda to Vol. 1 and Vol. 2, pt. 1.* N. Y., Interscience, 1956. pp. 1209-2088.

This volume completes the review of photosynthesis which the author began in 1938, vol. 1 being published in 1945 and vol. 2, pt. 1 in 1951. A number of topics have been omitted, among them the problems of large-scale culturing of microscopic algae for food and other purposes, and some of the most recent developments; but in general these three volumes form the most complete coverage to date of this rapidly enlarging field. In vol. 2, pt. 2, the discussion of the kinetics of photosynthesis is brought to a close with chapters on the temperature factor, the pigment factor and time effects. The Addenda includes the following topics: photochemistry of chlorophyll (in solution and in chloroplast preparations); chemical path of carbon dioxide reduction; structure and composition of chloroplasts; chemistry of pigments; spectroscopy and fluorescence of pigments; and the kinetics of photosynthesis, the last bringing up-to-date the subject of maximum efficiency. Illustrated, with author and subject index.

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Robinson, Nathan. "An occulting device for shading the pyrheliometer from the direct radiation of the sun." *Bull. Am. Meteor. Soc.* 36(1): 32-34. January 1955.

Describes an occulting device, developed by the author, which allows the pyrheliometer to measure diffuse sky radiation by cutting out the direct solar radiation. The author's device overcomes limitations of previous devices developed by the U.S. Weather Bureau and H. H. Kimball.

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Stephens, Ruth E., Ke, Bacon, and Trivich, Dan. "The efficiencies of some solids as catalysts for the photosynthesis of hydrogen peroxide." *J. Phys. Chem.* 59: 966-69. September 1955.

A number of solids were studied as catalysts for the photoproduction of hydrogen peroxide and of these, cadmium sulfide was found to be the most efficient. In monochromatic light, it was shown in the cases of zinc oxide, cadmium sulfide and cadmium selenide that the catalytic efficiencies extend to the absorption limit. A relation of the catalytic efficiency to the crystal structure, semiconducting and photovoltaic properties of the catalyst is indicated. It is suggested that zinc oxide and the other catalytic

solids should not be abandoned as devices for capturing solar energy in a form capable of transfer to some chemical system. (authors' abstract)

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Symposium on High Temperature — a Tool for the Future, *Berkeley, California,* June 1956. *Proceedings of the Symposium.* Sponsored by Stanford Research Institute; University of California. Menlo Park, Calif., Stanfor Research Institute, c1956. 218 pp.

These proceedings, covering three aspects of high temperature — methods for reaching high temperatures, materials for containing high temperatures, and processes occurring at high temperatures — include, in addition to much valuable information of a general nature, two papers dealing in part with solar furnaces. In the paper "Images of very high temperature sources", Joseph Farber deals in passing with the sun and solar concentrators as a guide to the use of earthly sources. In "Some considerations for the selection of materials for containing high temperatures", Tibor Laszlo points out the advantages of the solar furnace in eliminating difficulties due to the container and environment materials. Illustrated.

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Tabor, H. "Selective radiation. I. Wavelength discrimination. II. Wavefront discrimination." *Bull. Research Council of Israel* 5A(2): 119-34. January 1956. (Paper presented at the Tucson Conference on Solar Energy — the Scientific Basis, October-November, 1955.)

I. Initial experiments have shown that it is possible to produce surfaces which appear black but which have low emissivities at temperatures of a few hundred degrees C. Such selective surfaces should make possible the construction of solar energy devices of high efficiency with little or no optical concentration being required.

II. Because of the difference in form between direct solar radiation and thermal radiation from a heated body, it is possible, using optical principles, to construct a "solartrap" which will permit solar radiation to enter an enclosure while preventing thermal radiation from leaving it. Used as the cover of a flat plate solar energy collector, it provides a low effective emissivity and hence permits higher collection temperatures. Used as a "window" for a sun-heated house, it provides a transparent wall of low overall heat transfer coefficient. (author's abstracts)

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——— "Solar energy collector design." *Ibid,* 5C(1): 5-27. December 1955.

The possibility of making solar energy collectors of high efficiency by use of selective black surfaces has prompted a re-statement of the problem of collector design. By means of two parameters, the overall transmission efficiency and the cut-off intensity, it is possible to determine the performance of a collector under various conditions of use. The concept of retention efficiency permits the construction of generalized yearly average efficiency curves from which the influence of a change in some design parameter is quickly seen.

Computations show that it should be possible to produce low pressure steam without optical concentration, and high pressure steam with a small degree of concentration. (author's abstract)

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——— "Solar energy machines: engineering and economic aspects of the principle of selective radiation." Paper presented at the 5th World Power Conference, Vienna, 1956. 14 pp.

The absorption of solar energy and its conversion to power by means of a heat engine have not been economically viable due to the low collection efficiency unless expensive optical concentration is employed. By use of the principles of selective radiation — which permit the production of black surfaces of low effective emissivity —the efficiency of collection can be improved, resulting in an overall improvement factor of about three, thus bringing the solar power station — with superheating by fuel — close to economic viability. Reference is made to the methods of computing collector efficiencies, in particular the yearly average. (author's abstract)

Threlkeld, J. L. & Jordan, R. C. "Solar radiation during cloudless days." *Heat. Pip. Air Cond.* 27(2): 117-22. February 1955.

This paper presents the results of research on the incidence of solar and sky radiation during cloudless days on horizontal, south-facing vertical and south-facing tilted surfaces. Calculated curves based upon an assumed standard summer atmosphere and an assumed standard winter atmosphere are presented. Comparisons of the calculated curves with recorded clear day radiation measurements are made for Lincoln, Neb.; Madison, Wis.; Columbia, Mo.; Rapid City, S.D.; Nashville, Tenn.; and Blue Hill, Mass. (authors' abstract)

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Trombe, Félix. "Composite mirrors of large area in particular for concentrating solar energy." *U.S. Patent* 2,707,903. May 10, 1955.

This patent deals with the construction of a large area, composite curved mirror, of the type used in large solar furnaces. Each of the elementary mirrors consists of an elastically deformable plate which is given, by mechanical deforming means, the shape of the corresponding portion of the theoretical surface of the large mirror. In this particular case, the theoretical surface is a paraboloid of revolution. The elementary mirrors, trapezoidal in shape, are mounted on a framework, as described in the patent, to form substantially the theoretical surface of the large mirror. Illustrated.

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——— "Self-regulating automatic heliostat reflecting mirror device." *U.S. Patent* 2,712,772. July 12, 1955.

This invention is a device for maintaining a beam of rays, and in particular sun rays, in a fixed direction, giving a continuous and progressive adjustment without oscillation. A flat mirror (heliostat) is used to reflect the rays in a fixed direction; the power elements which give the heliostat the desired position in relation to the sun are operated by liquid under pressure. The feed of this liquid is controlled by a valve which is itself operated in response to currents supplied by photoelectric cells under the effect of the sun's rays. The flow rate of the liquid under pressure therefore depends on the intensity of the current supplied by the light-sensitive cells. Illustrated.

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Trombe, Félix and Foex, Marc. "Préparation de zircone pure par fusion alcaline du zircon au four solaire." *Compt. Rend.* 240(11): 1225-27. March 14, 1955. (Preparation of pure zirconia by alkaline melting of zircon in the solar furnace.)

Describes the extraction of zirconia (ZrO_2) from zircon (SiO_4Zr) in the solar furnace of Montlouis, which permits temperatures high enough for alkaline melting without contamination of the product being treated.

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——— ——— "Sur un nouveau procédé de traitement des métaux à l'aide de l'énergie solaire." *Compt. Rend.* 240 (2): 196-98. January 10, 1955. (A new process for the treatment of metals by means of solar energy.)

The authors describe the composition and construction of the refractory lining of a centrifugal furnace using solar energy to produce homogenous metal ingots. Illustrated.

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Ward, G. T. "Performance of a flat-plate solar heat collector." *Chart. Mech. Engr.* (London) 2: 293-95. 1955.

An orthodox flat-plate solar heat collector has been constructed which is capable of being manufactured cheaply on a large scale. A simple relation has been established between the efficiency of the collector, the plate temperature and the rate of insolation for constant rates of flow of circulating water. Performance charts have been constructed enabling an assessment to be made of the practicability of using solar energy in the tropics for the production of heat and power. (author's abstract)

Whillier, Austin. "The determination of hourly values of total solar radiation from daily summations." *Arch. Meteor. Geophys. Bioklimatol.* 7(2): 197-204. 1956.

Curves, based on measured total (direct plus sky) solar radiation data for several stations in the Union of South Africa, are presented which enable the hourly distribution of total solar radiation on a horizontal surface to be determined for any locality, and any time of year on a long-term basis. In addition, a graph is given showing the fraction of the daily total radiation which is received between stated hours, together with curves for four stations for estimating the difference between morning and afternoon total radiation for hour-pairs symmetrical about noon.

Although based on South African solar radiation data, the curves are presented in a form convenient for use, as a first approximation, for localities anywhere in the world, and for any time of year. They are applicable for long-term averages as well as for cloudless days. (author's abstract)

Yellott, John I. "Power from solar energy . . . some fundamental factors." Paper presented at the ASME Fall Meeting, Denver, Colorado, September 10-12, 1956. 14 pp. (To be published in *Trans. ASME.*)

Following a brief historical introduction, the paper points out the need for solar energy to supplement fossil fuels and nuclear power. The nature of solar radiation is described, and methods are given for estimating the amount available at any particular location. Flat plate and concentrating collectors are discussed, and recent technical advances are reported, including selective surface coatings and new tube-in-sheet materials. Cycles and prime movers are considered. Need for water in vapor cycle condensers indicates usefulness of hot-air engines. High thermal efficiency is advocated as a mean for reducing fixed charges by cutting size of collectors and rejectors. Illustrated. (author's abstract)